SOLUBLE SILICATES AND UV-B RADIATION EFFECTS ON THE GROWTH, NUTRIENT CONCENTRATION, AND YIELD OF SUGARCANE

BY

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DEDICATION

To the memory of my late father, Hassan El-Awad El-Kakar;

To my mother, Batoul Abdel Gaffar;

And to my wife Maimoona Osman Mohamed El-Amin,

To all of whom I owe my success,

And to my son Hassan.

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SOLUBLE SILICATES AND UV-B RADIATION EFFECTS ON THE GROWTH, NUTRIENT CONCENTRATION, AND YIELD OF SUGARCANE

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Two experiments were conducted to investigate the effects of several soluble silicates and supplemental UV-B irradiance on the growth and yield of sugarcane (a complex trispecies hybrid of *Saccharum*), variety C.P. 63-588, grown in an organic soil.

In the first experiment sugarcane seedlings were allowed to grow inside the greenhouse under enhanced UV-B irradiance provided by fluorescent sun lamps. The UV-B treatments consisted of 2, 3, and 4 sunburn units per hour (S.U./hr) and Mylar S control. Three Si treatments (0, 68, and 136 g Na silicate per 40-liter pot), each replicated 5 times, were imposed within each UV-B treatment in a nested design. Sugarcane seedlings also were allowed to grow inside and outside the greenhouse without exposure to supplemental UV-B irradiance

for comparative evaluation. Completely randomized designs were used with 3 Si treatments and 5 replications. Plant and first ratoon crops were studied to investigate effect of treatments on growth and yield of the crop.

Plant height, stem diameter, leaf area, and dry-matter yields of both plant and ratoon crops were significantly increased by Si. Addition of Si also protected plants against stem borer (*Diatraea saccharalis* (F)). Significant reduction in growth and yield was observed when plants were exposed to UV-B radiation. The 4 S.U./hr UV-B dose reduced dry-matter yield of plant and ratoon crops to 85 and 42% of the control, respectively. However, the plants showed no symptoms of leaf freckling. Plants grown outside the greenhouse without Si experienced severe leaf freckling although they were not exposed to supplemental UV-B irradiance. They also produced more tillers, especially when Si was added. Plants grown inside the greenhouse did not tiller even with the top rate of Si.

The second experiment was conducted in the field to study the response of sugarcane to four rates (5, 10, 15, 20 metric tons per hectare, MT/ha) of three different silicate materials (Fla slag, TVA slag, cement). A factorial experiment was installed in a randomized complete block design within a commercial field using 79.2 m^2 plots. Growth, nutrient concentration in the leaf, cane and sugar yields, and soil composition were studied in both plant and ratoon crops. Growth parameters and soil parameters were measured

one time each year while nutrient concentration was studied three times a year.

Application of soluble silicates increased millable stalks, plant height, stalk diameter, chlorophyll content of the leaf, and cane and sugar yields in both plant and ratoon crops. Leaf freckling was greatly reduced in treated plots. Addition of 15 MT material/ha increased sugar yields by 12.6 MT/ha for the two crops. The yield data tend to support the idea of the essentiality of Si, and point to its role in the production of more tillers, more efficient photosynthesis, and correction of leaf freckling. There were no differences in cane and sugar yields among the three materials in spite of their different Si contents. Plant and soil P were enhanced by Fla and TVA slags but were slightly reduced by cement.

CHAPTER 1

INTRODUCTION

Silicon is one of the most dominant elements in the ash of plants, especially grasses and cereals. Although the element improves the growth and yield of many crops, it is not considered essential for all plants. However, its essentiality for the growth and development of *Equisetum arvense, Cladophora glomerata, Synura petersenii,* and *Cylindrotheca fusiformis* has been proved beyond doubt (Chen and Lewin, 1969; Darley and Volcani, 1969; Klaveness and Guillard, 1975; Moore and Traquair, 1976). Addition of Si in the form of soluble silicates increases the yield of many agronomic crops including sugarcane, rice, sunflower, sugar beet, and others. Yoshida et al. (1959) showed that Si did not directly increase dry matter production of the rice plant provided its concentration in the plant was not less than 0.03%. Thus, the beneficial effects of soluble silicates applied to the field differ from the problem of the essentiality of Si.

Growth and yield of sugarcane have been substantially increased by soluble silicates. The mechanism by which sugarcane responds to soluble silicates is still a matter of controversy. In Hawaii, Clements and co-workers disregarded the idea of a Si critical level, and stated that soluble

silicates correct toxicities in the soil solution (Clements et al., 1974). They indicated that the presence of Fe^{2+}, Mn^{2+}, Al^{3+}, and Zn^{2+} in the soil solution causes sugarcane leaf freckling. Applications of soluble silicates precipitate these cations and remove them from the soil solution. Also, high concentrations of Si in sugarcane leaves prevent leaf freckling. In Mauritius, Wong You Cheong et al. (1971a) concluded that freckling was the foliar symptom of Si deficiency in sugarcane. Their study also suggested that solar UV-B radiation (280-320 nm) may be necessary for the development of the symptom. In Florida, Gascho (1978) stated that the development of leaf freckling is an expression of the plant's need for Si, silicate, or other factors supplied by applying soluble silicates. Once leaf freckling symptoms appear, they increase in intensity until they occupy as much as 50% of the total leaf area (Wong You Cheong et al., 1973). As a result, photosynthetic efficiency would be reduced and plant growth would be checked. Leaf freckling is either a degeneration of leaf tissue or a breakdown in a biochemical process due to Si deficiency.

Soluble silicates increase the solubility of soil P and decrease fertilizer P fixation by the soil (Roy et al, 1971; Silva, 1971). Phosphorus desorption by soils increases when soluble silicates are added to soils (Roy et al., 1971; Elawad, 1978). Yield increases following Si applications appear to be related to reactions of Si with P in the soil and in the plant (Silva, 1971). Conversely, Gascho (1978)

concluded that increased availability of P in the soil was not the cause of sugarcane response to soluble silicates in Florida mucks, but he added that Si might substitute for P in the plant. Increased P uptake associated with Si applications most likely results from increased dry-matter yields associated with soluble silicates rather than the other way around (Ayres, 1966). Slags, however, increase the level of P in the soil solution because they contain some P. But this is not related to yield increases associated with slags.

Additions of soluble silicates to sugarcane growing in low Si soils or nutrient solutions have been reported to enhance the plants' resistance against insects, diseases, and harmful radiation. Gascho (1978) and Wong You Cheong et al. (1971a) reported that leaf freckling developed on Si-deficient cane growing outside the greenhouse under direct sunlight. Inside the greenhouse, however, no such symptoms appeared, suggesting that solar UV-B radiation may be necessary for symptom development. The harmful portion of solar UV radiation (UV-C and portions of UV-B) is absorbed by the ozone layer found in the stratosphere. However, the present ozone level is subject to breakdown and depletion by several human activities and natural causes. This would be accompanied by increases in UV-B densities which might be harmful to plants and animals. The effect of supplemental UV-B irradiance have been investigated in several crops, but not in sugarcane.

The main objectives of the present studies were as follows:

(1) To investigate the effect of enhanced UV-B irradiance on the growth and dry-matter yield of sugarcane plants.

(2) To determine whether addition of a soluble silicate may protect the plants against supplemental UV-B radiation.

(3) To compare the growth of sugarcane inside and outside the greenhouse.

(4) To investigate the role of several levels of soluble silicates on the growth and yield of field-grown sugarcane.

(5) To evaluate effects of three sources of calcium silicate on plant and soil parameters.

(6) To identify the role of Si in plants.

CHAPTER 2
LITERATURE REVIEW

Responses of Plants to Silicon

Many investigators have reported beneficial effects of Si on the growth and yield of various plants. Additions of various compounds and materials containing Si to the soil improves growth and increases yields of sugarcane (*Saccharum sp.*), rice (*Oryza sativa*), sorghum (*Sorghum bicolor*), millet (*Setaria italica*), corn (*Zea mays*), wheat (*Triticum aestivum*), barley (*Hordeum vulgare*), sunflower (*Helianthus annus*), tomato (*Lycopersicon esculentum*), beet (*Beta vulgaris*), cucumber (*Cucumis sativus*), tobacco (*Nicotiana tobaccum*), beans (*Phaseolus vulgaris*) and many other crops. However, Si is still classified as a nonessential element because its essentiality has not been proved from a biochemical standpoint.

Species

Liebig in about 1840 regarded Si as an essential element and classified crop plants as silicon plants, calcium plants, or potassium plants on the basis of their predominant ash constituent (Palladin, 1923). Plants are also classified as silicophile or nonsilicophile based on their ability to

accumulate Si in their tops (Takahashi et al., 1976). It is generally accepted that grasses, sedges, and other members of Poaceae contain 10 to 20 times the concentration of Si found in legumes and other dicotyledons (Mengel and Kirkby, 1978; Russell, 1973). Scanning electron microscopy, electron probe microanalysis, and nondispersive X-ray microanalysis, as well as acid digestion of leaf and stem tissue, show that Si is widely distributed in the shoots of grasses, typically concentrated in stomatal guard cells, Si cells, trichomes, and tangential walls of long epidermal cells (Hansen et al., 1976; Kaufman et al., 1972a,b; Lau et al., 1978; Soni et al., 1972). Jones and Handreck (1967) grew different crops in a sandy loam of pH 6.0 and containing 21 ppm Si in solution. They found the following Si concentrations: rye (*Secale cereale*), 1.12; ryegrass (*Lolium mulliforum*), 1.09; oats (*Avena sativa*), 0.95; peas (*Pisum sativum*), 0.12; mustard *Brassica campestris*), 0.07; crimson clover (*Trifolium incarnatum*), 0.06 percent. The concentration of Si in different plants is reported to decrease in the order: grains $\geq$ grasses $\geq$ vegetables and fruits $\geq$ legumes (Thiagalingam, 1971). The legume *Desmodium aparines* L. (=*D. intortum M.*) is an exception since it accumulates high levels of Si in its shoot (Khalid, 1974). The characteristically low concentration of Si in legumes and other dicotyledons suggests that these plants have some mechanism of excluding Si from the transpiration stream, either within the root or at its external surface. Pineapple *(Ananas comosus)*

is another crop which responds very poorly to the application of silicate materials (Thiagalingam et al., 1977). Silicon concentrations approaching 10 percent are common in Si rich plants such as rice, certain ferns, and horsetails (*Equisetum arvense*). At harvest time the straw of Japonica and Indica rice varieties contain more than 5.0 and 3.8 percent Si, respectively, when yields are satisfactory (Takijima and Gunawardena, 1969). Rice appears to have a special ability to absorb Si. Okuda and Takahashi (1965) reported that rice, grown in culture solution, absorbed monosilicic acid at a much higher rate than it absorbed water. Xylem sap from rice grown in the field was found to contain 187 to 374 ppm Si (Baba, 1957). Sudagrass (*Sorghum sudanense*) supplied with various silicate minerals contained more than 3.0 percent Si (Clements et al., 1974). In Brazil, Gallo et al. (1974) measured Si levels in many grass and forage crops including sugarcane, rice, maize, sorghum, oats, rye, wheat, bamboo (*Arundinaria gigantea*), and many forage grasses. The level of Si ranged between 0.8 and 1.93 percent. Jaragua grass (*Hyparrhenia rufa*), however, contained 3.91 percent Si.

<u>Essentiality vs. Nonessentiality</u>

Arnon and Stout (1939) stated that an element is said to be essential if it satisfies the following four criteria: (1) If the element is contained in a plant in amounts less than required, the plant cannot grow normally either at

vegetative or reproductive stages. The plant cannot complete its life cycle if the element is completely absent. (2) Symptoms caused by its deficiency are specific for it and can only be corrected by adding it. (3) The element must be involved directly in the nutrition of the plant. Effects of its application on plant growth are completely independent of improvement of environmental conditions. (4) The element is a cell component, or found in an enzyme essential for plant growth. So far it has been reported that Si satisfies at least the first two criteria (Mitsui and Takatoh, 1963; Comhaire, 1966).

Critical culture solution studies have been carried out recently to test the essentiality of Si by avoiding glass and other contaminants. Fink (1974) reviewed the literature on mineral nutrition of higher plants. He stated that Si together with Na, Co, and V would probably be added to the list of the 16 elements so far proved essential. The essentiality of Si for the growth and development of horsetail, *Cladophora glomerata*, *Synura petersenii* and the diatom *Cylindrotheca fusiformis* has been proved beyond doubt (Chen and Lewin, 1969; Darley and Volcani, 1969; Klaveness and Guillard, 1975; Moore and Traquair, 1976). Physiological and ultrastructural studies of cultures of the filamentous green alga *Cladophora glomerata*, demonstrated that Si was a required nutrient and a component of cell walls (Moore and Traquair, 1976). The investigators used Ge (germanium, an analogue of Si) to inhibit monosilicic acid metabolism.

Since Ge is not toxic to algae, the inhibition of the growth of *C. glomerata* is an indication that the alga requires Si. Chen and Lewin (1969) concluded that Si was essential for the healthy growth of *Equisetum arvense* L. Silicon-deficient shoots exhibited deficiency symptoms such as necrosis of branch tips and wilting or drooping of branches. In the diatom *Cylindrotheca fusiformis* Si was found to be required for DNA synthesis (Darley and Volcani, 1969).

The search for a physiological role of Si to justify its essential nature in higher plants has been undertaken by many researchers. Lipman (1938) found that sunflower and barley were definitely benefited, especially as regards to seed production, by the presence of Si in the culture medium. Raleigh (1939) conducted an experiment which indicated that Si was an indispensable chemical element for the growth of the beet plant. Woolley (1957) concluded that if Si was essential for the growth and development of the tomato plant, less than 0.2 mg Si/g of dry weight was required. The beneficial effects of Si in the growth of the rice plant have been reported by many workers (Ishizuka, 1971; Maxwell et al., 1972; Okamoto, 1969; Yoshida et al., 1969). Rice responses to Si were recently reviewed by Elawad and Green (1979). Applications of silicate materials increased rice yields in Japan when the Si content of the straw at harvest time was less than 5.0% (Ishizuka, 1971), However, Yoshida et al. (1959) showed that Si did not directly increase the dry matter production of the rice plant during vegetation growth

provided that the Si content of the plant was not less than 0.03%. Thus, the beneficial effects of Si application on rice yields in the field differ from the problem of its essentiality. Engel (1953) investigated the nature of Si compounds in the culm of rye and reported that 20 percent of total Si was present in the cellulose framework. He also identified the presence of a Si galactose complex which might be important in metabolism.

Applications of silicates benefit sugarcane grown in different soils and climates. Silicon is reported to have some biochemical roles in sugarcane. It inhibits the action of the enzyme invertase (Alexander, 1968, 1969; Wong You Cheong et al., 1971b), increases photophosphorylation in both roots and leaves (Wong You Cheong and Chan, 1973), and increases the rate of photosynthesis (Wong You Cheong et al., 1971b). Clements et al. (1974) suggested that Si has a physiological role in preventing localized accumulation of toxic ions such as Fe^{2+}, Mn^{2+}, and Al^{3+}. Ayres (1966) and Wong You Cheong et al. (1971a) claimed that sugarcane has a basic Si requirement which should be met for satisfactory growth and yield. Wong You Cheong et al. (1971a) claimed that sugarcane leaf freckling is a Si deficiency symptom and hypothesized that applications of Si might protect the cane plant from deleterious solar UV-B radiation.

The essentiality of Si for plants is difficult to determine because the so called "Si-free cultures" may receive sufficient Si from seeds, nutrient salts, distilled water, culture vessels, and atmospheric dust.

Relationship with Soil Properties

Silicon is the second most abundant mineral element in the lithosphere after oxygen, and mineral soils contain about 32% Si by weight. The element occurs in soils in primary silicate minerals, secondary aluminosilicates, and various forms of SiO_2. The most common forms of SiO_2 include: amorphous SiO_2, coesite, tridymite, cristobalite, and quartz. Amorphous SiO_2 is the most soluble form and it occurs in soils both as a consequence of weathering and as a product of vegetation. The least soluble form of SiO_2 is quartz, which is dominant in most sandy soils. Under some conditions silicon can be deposited between soil particles to give a "silica pan" as happens in some sandstones in which silicon binds the sand particles together. Silicon is also present in hydrated forms such as chalcedony and opal. These bodies are called phytoliths, and usually accumulate in grassland soils.

Silicon is present in the soil solution almost entirely as the simple molecule monosilicic acid, $Si(OH)_4$ (Alexander et al., 1954). This is the form of Si taken up by plants and diatoms (Jones and Handreck, 1965a). The first dissociation constant of this acid has a pk of 9.7, which indicates that the silicate anion is not present in any appreciable concentrations in the solution of normal agricultural soils. The amount of soil Si available to plants is relatively very small and varies with different soils (McKeague and Cline, 1963, Jones and Handreck, 1963; Hingston et al., 1967, 1968).

Monosilicic acid in soils is in equilibrium with a solid phase, for if a soil is extracted with water, and then left moist, the concentration of Si in the soil solution will return to its original value (Alexander et al., 1954). The solubility of SiO_2 minerals in terms of $Si(OH)_4$ ranges from $10^{-2.74}$ $\underline{M}$ (amorphous SiO_2) to 10^{-4} $\underline{M}$ (quartz) (Lindsay, 1979). The average activity of monosilicic acid in soil suspensions was reported to be $10^{-3.1}$ $\underline{M}$ (Elgawhary and Lindsay, 1972; Sadig et al., 1980). This approximately is equal to 28 ppm Si. In highly weathered soils depletion of free SiO_2 may leave sesquioxides of iron and aluminum as the major residual minerals. In such soils the solubility of monosilicic acid drops below that of quartz. In a saturated solution of pure amorphous SiO_2 the concentration of monosilicic acid (at 25° C) is 56 to 65 ppm Si. In soil solutions monosilicic acid is commonly present to the extent of 14 to 19 ppm Si (Jones and Handreck, 1963, 1965b).

Much controversy has prevailed concerning the solubility of monosilicic acid in soil and how it is affected by pH. Raupach (1957) observed in some Australian soils that the concentration of Si decreased with increasing pH from 4 to 9. A similar finding was reported by Jones and Handreck (1965b) who observed that the concentration of monosilicic acid dropped from 33 to 11 ppm Si in an Australian soil when its pH was raised from 5.5 to 7.2. Beckwith and Reeve (1963, 1964), after shaking several soils with solutions

containing varying concentrations of monosilicic acid, observed that the residual concentration of monosilicic acid was controlled by an adsorption mechanism and steadily increased with acidification below pH 8-9. In a recent study Khalid, Silva and Fox (1978) found that water-soluble Si in a Gibbsihumox soil decreased as pH increased. This is attributed to the fact that monosilicic acid in soils is adsorbed on the surface of iron and aluminum hydrous oxide films by ligand exchange (Beckwith and Reeve, 1963; Jones and Handreck, 1963; McKeague and Cline, 1963). This reaction is said to be pH dependent. Thus, the greater the surface area of the active aluminum and ferric hydroxide films on the soil particles, and the higher the pH up to 9.5, the more tenaciously will the soil adsorb monosilicic acid, and the lower will be its concentration in the soil solution. It is evident then that waterlogging a soil, as is done with flooded rice, is likely to increase its water soluble Si, presumably due to its release from hydrated ferric oxide surfaces. At times, there appears to be a layer of monosilicic acid or silica gel at the surface of the flood water, especially noticeable in greenhouse pot experiments (Elawad and Green, 1979). Treatments which remove free sesquioxides from a soil are also expected to release monosilicic acid. Many investigators, on the other hand, reported that the solubility of monosilicic acid was constant in many agricultural soils with different pH values (Iler, 1955; Jones and Handreck, 1967;

Lindsay, 1979; Sadig et al., 1980). Jones and Handreck (1967) found that the solubility of monosilicic acid was independent of pH in the range 2 to 9, but it increased sharply above pH 9 due to the formation of the silicate species SiO_4^{4-}. Lindsay (1979) showed very clearly that the solubility of monosilicic acid maintained in soils by various forms of silica was independent of pH. However, he indicated that the solubility of the other silicate ions, namely $H_3SiO_4^-$, $H_6Si_4O_{12}^{2-}$, $H_2SiO_4^{2-}$, $HSiO_4^{3-}$ and SiO_4^{4-}, increased sharply with increased pH. Nevertheless, the contribution of these ions to Si in soil solution is practically zero as compared to the contribution of monosilicic acid.

The controversy regarding the solubility of Si in soils can be avoided by extracting soils with 0.02 M $CaCl_2$ in order to keep colloidal silica flocculated during extraction and filtration of soils (Elgawhary and Lindsay, 1972). When this technique is used, Si in the soil solution corresponds more closely to the levels of monosilicic acid expected from solubility predictions (Lindsay, 1979). Kittrick (1971) showed that the equilibrium between kaolinite and montmorillonite will maintain about 10^{-3} M $Si(OH)_4$ in solution (28 ppm Si). Elgawhary and Lindsay (1972) measured the solubility of silica in two soils in which equilibrium was approached from both undersaturation and supersaturation. The calcareous soil supported 25 ppm Si in solution, while the acid soil supported only 19 ppm. They concluded that the solubility of SiO_2 (soil) ($10^{-3.1}$ M) was intermediate between quartz

(10^{-4} $\underline{M}$ or 2.8 ppm Si) and amorphous silica ($10^{-2.74}$ $\underline{M}$ or 51 ppm Si), and it controlled Si solubility in soil solution.

The solubility of monosilicic acid in the soil solution is sometimes directly related to the availability of soil phosphorus to plants. It was reported that the most efficient method of predicting the response of wheat to a P fertilizer, for a group of East African soils, was to determine the amount of water-soluble or 1% citric acid-soluble Si in the soil (Birch, 1953; Garberg, 1970). The response to applied P decreased linearly with the increase of extracted Si up to a certain level, after which there was no response to P. Khalid (1974) reported that modified Truog-extractable P was significantly higher at 1660 ppm Si than at zero Si five years after TVA slag applications.

Studies of the movement of Si in soils revealed that considerable Si applied to soils might be lost by leaching (Roy et al., 1971; Khalid, 1974). The extent of leaching depends on the amount of water percolating through the soil, the soil's capacity for Si sorption, the amount of silicate material applied and the soil pH. Hagihara (1971) working with a Gibbsihumox soil in Hawaii reported a loss of only 3 percent of applied silicate after 95 inches of water percolated through a 12-inch soil column.

Many extracting solutions are used to measure the extent of soluble silicon in soils. These extractants include distilled water, 0.02 N $CaCl_2$, 0.5 N NH_4OAc, 0.01 N H_2SO_4 and others. The soil/extractant ratio and the duration of

shaking vary with different extractants. The critical level for soil extractable Si depends on the extractant used. Ayres (1966) indicated that the critical level for Si was around 50 ppm Si for low Si Hawaiian soils extracted with 0.5 M NH_4OAc (pH 4.8). In some Mackay Australian soils the critical levels are 20 and 100 ppm. Si when 0.02 N $CaCl_2$ and 0.01 N H_2SO_4 extractants are used, respectively (Haysom and Chapman, 1975). In Florida organic soils the critical level is about 30 to 50 ppm Si extracted by 0.5 N NH_4OAc (pH 4.8).

Relationship with Plant Composition

Plant Si is almost insoluble and perhaps of little biochemical significance (Fox et al., 1969). It is deposited in epidermal cells and cell walls of plants in the form of silica gel (a form of hydrated amorphous silica, $SiO_2 \cdot nH_2O$, or polymerized silicic acid). In the xylem sap Si is entirely in the form of monosilicic acid. Polymerized silicic acids in plants are strongly bound to cellulose forming a silicocellulose membrane and can only be separated after the cellulose is dissolved (Maxwell et al., 1972). Many silicophile plants such as sugarcane and rice form a silica layer under the cuticle referred to as "cuticle-silica double layer" (Yoshida et al., 1962).

Silica gel in plants is usually immobile and does not supply Si to other parts of the plant. Soluble plant Si usually is not abundant in plants. Dry ashing usually changes

the properties of plant Si while wet digestion gives good results without affecting the chemical and physical properties of Si. Nitric acid or a mixture of nitric and perchloric acids can safely be used for wet digestion. Sulfuric acid, being a dehydrating acid, cannot be used for wet digestion as it changes the properties of Si (Lewin and Reimann, 1969).

The distribution of Si in plant parts is very much dependent on type of plant. Mature and older parts usually contain more Si than younger parts. Leaves of sugarcane have the highest level of Si compared to other plant parts (Gallo et al., 1974). Both total and soluble plant Si are higher in sugarcane leaf sheaths than in blades while total Si is higher in the leaves than in the internodes (Fox et al., 1968). For plants high in Si such as rice and sugarcane more than 90 percent of the Si occurs in the tops.

Scanning electron microscopy and electron probe microanalysis show that Si is widely deposited in the shoots of grasses, typically localized in trichomes, Si cells, and walls of long cells in the epidermal system (Hansen et al., 1976; Lau et al., 1978; Soni et al., 1972). In sugarcane most of the Si is normally deposited in the outermost cells such as trichomes, bulliform cells, and stomatal elements.

Thiagalingam (1971) reported that Si concentration in xylem exudates of sugarcane was greater than Si levels in the external solution. This indicated that active transport rather than mass flow was responsible for Si uptake.

Fox et al. (1969) concluded that Si uptake by sugarcane plants was not associated with transpiration, however, the distribution of Si within the plant was a passive process closely related to transpiration.

Sugarcane Leaf Freckling

The so-called "leaf freckling" of sugarcane has been reported in field-grown cane in many parts of the world including Hawaii, South Africa, Mauritius, Australia and Florida. The malady is found to decrease sugarcane and sugar yields (Clements et al., 1974; Gascho, 1977, 1978; Gascho and Andreis, 1974; Wong You Cheong et al., 1971a).

Freckling is found on cane plants growing on very acid, cold and poorly drained soils (Clements et al., 1974). It manifests itself on sugarcane leaves as small elongated yellow spots which become reddish, then brown, and finally dark gray brown and necrotic as the leaf ages. Meanwhile, the spots enlarge and the necrosis spreads. The distal surfaces of the leaves, particularly those exposed to full sunlight, develop mirrorlike, silvery spots. Finally, the spots become reddish and the older leaves die prematurely (Clements et al., 1974). Affected plants are less efficient in performing photosynthesis not only because they have less number of leaves but also because many leaves are freckled. A similar malady has been reported on barley grown in a culture solution void of Si (Williams and Vlamis, 1957). They reported that the necrotic leaf spotting was caused by

the development of localized concentrations of Mn in Si-deficient leaves. In Hawaii, leaf freckling of sugarcane is attributed mainly to the presence in the soil solution of ferrous iron salts together with salts of Al, Mn and Zn (Clements et al., 1974). Root growth is strikingly reduced, resulting directly in reduced top growth. Sugarcane leaf freckling has also been attributed to high levels of Mn and high Mn/Si ratio of the leaf sheath (Clements, 1965b) and to low Si and high Fe contents of the leaves (Clements et al., 1974). Applications of calcium silicate have been found to decrease concentrations of Fe, Mn and Al in the leaves of sugarcane (Clements, 1965b; Clements et al., 1967). This has led Clements et al. (1974) to suggest that Si must have a physiological role in preventing localized accumulations of toxic ions which cause necrotic leaf spotting or freckling. Fox et al. (1967a), however, observed severe freckling on sugarcane leaves having a favorable Mn/Si ratio. This suggested that sugarcane leaf freckling was caused by something other than accumulation of toxic elements. In Florida, Gascho and Andreis (1974) reported no effect on the concentrations of Fe, Mn, Zn, Cu, and other nutrient elements in the cane leaf tissue by calcium silicate applications although leaf freckling was reduced and sugarcane and sugar yields were increased. It seems that the development of freckled leaves is an expression of a plant's need for Si, silicate or other factors supplied as a result of the application of a soluble silicate source.

Gascho (1978) stated that freckling of sugarcane was a symptom of the need for Si.

In Mauritius, Wong You Cheong et al. (1971a) observed that leaf freckling developed after 75 days on Si-deficient cane receiving direct sunlight. Under a Perspex or glass roof, however, no such symptoms appeared, suggesting that UV-B radiation (280-320 nm) from the sun might be necessary for symptom development. Deficiency symptoms were evident only on the physically upper surface and rapidly disappeared after treatment with Si. They concluded that freckling was the foliar symptom of Si deficiency in the sugarcane plant. In another experiment Wong You Cheong et al. (1973) grew sugarcane cuttings in pots containing Arnon and Hoagland solution. They supplied Si as sodium silicate at concentrations of 50, 100 and 200 ppm Si. They observed that leaf freckling symptoms only developed on plants that received no Si.

Response of Sugarcane to Silicate Materials

More Si is absorbed by sugarcane than any other mineral element. In a 12-month crop, sugarcane accumulated about 380 kg/ha of Si in the shoot, compared to 362 kg K and 140 kg N (Ayres, 1930). The discovery that silicate materials, applied to the soil, increased sugarcane and sugar yields was an indirect one. The initial discovery was reported in Mauritius in 1937 when finely crushed basalt was applied in an effort to rejuvenate highly weathered sugarcane soils

(Martin-Leake, 1958). In 1947, Villiers (1961) conducted experiments with rates of 100, 200, and 400 MT/ha of crushed basalt. He obtained total cane yield increases for four crops (one plant crop plus three ratoon crops) of 44.4, 65.8, and 81.8 MT/ha, respectively. Although the author did not suggest the role played by the basalt, he did mention that the material was a source of soluble Si. However, the increase in tonnage mentioned above was not attributed to soluble Si in basalt. Then, the work by Halais and Parish (1963) showed that it was, indeed, soluble Si in the basalt which caused the increase in cane yield.

The first direct use of silicate materials to improve the growth of sugarcane took place in Hawaii in 1960 when Dr. G. E. Sherman, of the University of Hawaii, and his students worked with the possible use of a low-phosphate slag from the TVA phosphate process (TVA slag or calcium silicate) to improve the fertility of certain aluminous humic ferruginous latosols (Samuels, 1969). During 1963 Dr. H. F. Clements started a series of experiments to investigate the role of Si in the growth of sugarcane (Clements, 1965a). He used two silicate materials, TVA slag (16.6% Si and 27.5% Ca) and a volcanic cinder from Kau, Hawaii (30.7% Si and 1.5% Ca). The TVA slag was applied at rates of 4.5, 9, 13.5, and 18 MT/ha of total material. The Kau cinder was applied at the same Si rate as the TVA slag. Of the two materials used, only the TVA slag gave significant increases in cane and sugar yields and reduced freckling.

The most economic increase in cane and sugar yields was obtained with 9 MT/ha of TVA calcium silicate slag (Clements, 1965a). The beneficial effects of TVA slag were mainly attributed to decreases in plant Mn and in the ratio Mn ppm/SiO_2% (Clements, 1965b). Clements et al. (1967) tried various silicate materials such as olivine cinders, basalt dust, Hawaiian silicate, trachyte, volcanite, cement, and electric- and blast-furnace slags. Cement is a good source of soluble Si, although it has the disadvantage of setting and has a very high Ca content, which may cause severe chlorosis by raising the soil pH to levels which are too high for optimum growth and absorption of micronutrients. The electric-furnace slag (TVA slag) is identified as primarily gehlenite ($Ca_2Al_2SiO_7$) with some pseudowallastonite ($CaSiO_3$). The Hawaiian silicate, produced by the Hawaiian Cement Company, is primarily calcium metasilicate ($CaSiO_3 \cdot nH_2O$). It is 20 percent more effective than TVA slag (Clements et al, 1967). Dr. A. S. Ayres, of the Hawaiian Sugar Planters' Association (HSPA), applied 2.8, 5.6, and 11.2 MT/ha of calcium silicate slag to sugarcane on low-Si Hawaiian soils (Ayres, 1966). The most economic percent increase in sugar yield was obtained with the application of 5.6 MT/ha material. However, cane yield continued to increase significantly with the application of the top rate. No increase in sugar was obtained by additions of calcium silicate on soils which had more than 50 ppm Si extracted by 0.5 M NH_4OAc (pH 4.8). Fox et al. (1967b) indicated that

a water-soluble Si content, for some Hawaiian soils, of less than 2 ppm might be indicative of a low Si soil. Silicon deficiency in sugarcane might occur when water-soluble soil Si was less than 0.9 ppm. Application of 4.5 MT/ha of TVA slag increased sugar yields by 12 MT/ha/25 months in a field where phosphate-extractable soil Si ($Ca(H_2PO_4)_2$) and trichloroacetic acid (TCA)-extractable Si of sugarcane leaf sheath were about 20 ppm each. Samuels (1969) reported that 9 MT/ha of TVA slag, applied to low-Si soils in Puerto Rico, resulted in the most economical increase in cane and sugar yields.

Fifteen kinds of silicate slags have been tested on sugarcane fields in Taiwan since 1961 (Shiue, 1973). Their effects were found to depend upon the source of the materials and their content of minor elements, as well as on soil acidity. When less than 37 ppm of soluble Si (0.5 $\underline{M}$ NH_4OAc, pH 4.8) occurred in the soil, the probability of a profitable increase in yield from silicate slag was 50 percent or more.

Ross et al. (1974) reported results of field experiments planted in 1967 in Mauritius. Two rates of calcium silicate, 7.1 and 14.2 MT/ha, were applied to sugarcane soils and yields of six crops (one plant crop and five ratoon crops) were compared to the control. They obtained total cane yield increases of 83.4 and 108.9 MT/ha for the six crops. The higher rate of calcium silicate gave slightly better cane yields than the lower rate, but the difference was not significant. The best response of sugarcane to applied calcium

silicate was obtained in the plant crop. No significant change in the sucrose content of the cane was observed with the application of calcium silicate. However, sugar produced per ha increased significantly with the application of 7.1 MT/ha of material.

In Florida, Gascho and Andreis (1974) applied TVA calcium silicate slag to low-producing organic and sand soils in two experiments, and an electric-furnace calcium silicate slag from Pierce, Florida, to a low-producing organic soil in a third experiment. They applied 1.1, 5.6, and 11.2 MT/ha Florida slag on an Everglades peat soil in one experiment, 4.5, 9, and 17.8 MT/ha TVA slag on another Everglades peat soil in another experiment, and 4.5, 9, and 17.8 MT/ha TVA slag on Immokalee fine sand in a third experiment. Sugarcane leaf freckling was reduced and cane and sugar yields were significantly increased by the application of both slags. Responses up to 3.9 MT/ha of sugar for three crops, where 11.2 MT/ha of Florida slag were applied on organic soil, and 4.8 MT/ha of sugar per year, on sand soil treated with 17.8 MT/ha of TVA slag, were reported. Application of 9 MT/ha of TVA slag on organic soil gave statistically similar cane and sugar yields as 17.8 MT/ha on sand soil. Leaf Si was positively and linearly correlated with slag rate and sugar production. In another study, Gascho (1977) concluded that a large proportion of Florida sugarcane located on the less productive muck and sand soils would apparently respond to applications of calcium silicate slag.

In an attempt to study the mechanisms of sugarcane response to Si in Florida, Gascho (1978) applied 409 g TVA slag (18.6% Si) per 20-liter pot (equivalent to 22 MT/ha) and 771 g reagent grade $Na_2SiO_3 \cdot 9H_2O$ (10% Si) per pot (38.9 MT/ha). The TVA slag increased length and fresh weight of plants while sodium metasilicate increased their length, number and fresh weight. Thus the response was attributed to Si.

The response of sugarcane to calcium silicate applications was investigated in Australia by many workers (Haysom and Chapman, 1975; Hurney, 1973). Application of 4 MT/ha of calcium metasilicate as cement increased cane yield from 99 to 124 and from 89 to 105 MT/ha in a sand soil and a silty clay loam soil, respectively (Haysom and Chapman, 1975). They reported that Si had no effect on sugar concentration in cane.

Many soluble silicate materials have been used, either as foliar spray or in nutrient solution, to stimulate the growth of sugarcane and other crops. Alexander et al. (1972) reported that 500 ppm Si as sodium metasilicate ($Na_2SiO_3 \cdot 9H_2O$) increased slightly total green weight and stalk length of sugarcane. Raleigh (1939) was inclined to regard Si as an essential element for beets when he obtained very large increases in the growth of both tops and roots of beets grown with pure K_2SiO_3. Plants grown without Si were more susceptible to damping off disease. Vlamis and Williams (1967) used 10 ppm Si as sodium metasilicate in their culture solutions. They reported that the addition of Si to the

solution prevented the appearance of Mn-toxicity symptoms in barley, rye, rice, and ryegrass. Wong You Cheong and Chan (1973) pre-tested sugarcane root segments with a nutrient solution containing 0.5m*M* Na_2SiO_3 for two days prior to incubation with ^{32}P. They observed a significant increase in the degree of phosphorylation although no effect was obtained on labelled phosphate uptake. Horst and Marschner (1978) studied the effect of Si on Mn tolerance of bean plants grown in water culture at different levels of Mn supply. Silicon was added as aerosil, 100 mg/liter nutrient solution. Aerosil contains about 46.6 percent Si. A Si concentration of 0.75 ppm was found after the addition of 100 mg aerosil/liter to the nutrient solution. For preparation of nutrient solutions with varied Si concentrations, 1 ml sodium tetrasilicate (Wasserglass) was dissolved in one liter water to give 200 ppm Si. This stock solution of Si was diluted and added to the nutrient solution. Growth depression and toxicity symptoms occurred at $5x10^{-4}$ m*M* Mn in nutrient solution without Si. After the addition of 100 mg aerosil/liter solution (0.75 ppm Si), the plants tolerated $5x10^{-3}$ m*M* Mn and, at a higher Si supply of 40 ppm (as sodium tetrasilicate), as much as 10^{-2} m*M* Mn in the nutrient solution without any growth depression. The decrease in Mn toxicity was attributed to increase in Mn tolerance of the leaf tissue.

Mechanisms of Response

Many mechanisms of plant response to applied silicate materials have been proposed (Comhaire, 1966; Gascho, 1978; Lewin and Reimann, 1969; Okuda and Takahashi, 1965; Silva, 1971; Wong You Cheong et al., 1971a). These include suppression of trace element toxicities in soil and plant, increased plant resistance to insects and diseases, reduced lodging, increased oxidation power of roots, improved P nutrition, better leaf disposition and more efficient use of sunlight, enhanced water use efficiency, correction of Ca and Mg deficiencies, protection of plants against deleterious UV-B radiation, and correction of leaf freckling in sugarcane.

Interactions with Phosphorus and Boron

The chemical similarities between Si, P and B indicate that the elements may interact with each other at the soil and/or the plant levels. The addition of soluble silicates to soils increases the solubility of soil P (Tuilin, 1936; Toth, 1939; Cooke, 1956; Raupach and Piper, 1959; Teranishi, 1968; Roy et al., 1971) and decreases fertilizer P fixation (Adlan, 1969; Silva, 1971). The release of soil P by Si is not due to anionic exchange between silicate in solution and adsorbed phosphate since silicate ion cannot exist in appreciable amounts in normal agricultural soils (Jones and Handreck, 1967; Lindsay, 1979). The results could be due to an increase in pH, which is known to free P from its

union with iron and aluminum. Monosilicic acid could decrease Al activity in soil solution and so prevent it from precipitating phosphate. It could also compete against phosphate for a place on the surface of hydrated sesquioxides (Jones and Handreck, 1967). Phosphorus desorption by soils has been found to increase when silicate materials are added to soils (Roy et al., 1971; Elawad, 1978). The effect of Si on P desorption or adsorption may be due to the interaction of Si with sorption sites, or due to the inactivation of Fe and Al by rendering them insoluble. The use of silicates also improves the efficiency of P fertilizers. Silicate materials exert a solvent action on phosphate fertilizers and render the P on them more available to plants. Most silicate slags which are commercially available contain some P.

Many research workers suggested the following possible effects for Si applications: (1) increased level of plant P, (2) increased root absorption of P, (3) more effective utilization of plant P, and (4) better P assimilation (Silva, 1971; Kudinova, 1974). Yield increases following Si applications were said to be related to reactions to this element with P in the soil and in the plant (Silva, 1971). Okuda and Takahashi (1962) claimed that Si inhibited the luxury consumption of P in the rice plant. Conversely, many investigators reported significant increases in crop yield and total P uptake due to Si applications (Suehisa et al., 1963; Hunter, 1965; Thiagalingam, 1971). Silva (1971) presented

strong evidence that Si had a role in P metabolism. Increased P uptake associated with Si applications most likely results from increased yields rather than the other way around. Ayres (1966) stated that increased P uptake by sugarcane with Si applications was due to higher yields resulting from the use of the silicate material. Gascho (1978) reported that the effects of silicate applications on P nutrition of sugarcane did not explain the positive responses to the materials in Florida. He concluded that increased availability of P in the soil was not the cause of sugarcane response to TVA slag or sodium silicate, but he added that Si might substitute for P in the plant. As a matter of fact P concentration in the above-ground plant tissue was reduced due to the application of soluble silicates as a result of increased soil pH. In an earlier investigation, Gascho and Andreis (1974) reported that P concentration in the leaf tissue of sugarcane was not appreciably affected by calcium silicate additions. Positive yield responses were obtained under both high and low P nutrition. This indicated that the response of crop to slag applications was probably not due to soil reactions that made P more available nor to better P metabolism in the plant. Silicon pre-treatment of root sections increased the levels of ^{32}P esters in both leaves and roots of sugarcane although no effect was obtained on labelled phosphate uptake (Wong You Cheong and Chen, 1973). When the concentration of Si in a pure culture solution was raised from 0 to 200 ppm, Si and P levels in the whole third

leaf of sugarcane changed from 0.03 to 1.24 and from 0.202 to 0.163%, respectively (Wong You Cheong et al., 1973). Increased P uptake following Si applications is an effect rather than a cause of increased yields (Silva, 1971).

Interactions between Si and B are not well understood as the precise functions of B in plants are still not certain. Studies on the function of B in plants implicate that the element is involved in RNA metabolism (Albert, 1965), in the biosynthesis of sucrose (Dugger and Humphreys, 1960) and as a modulator determining the level of activity of the pentose shunt (Lee and Aronoff, 1967). Boron also has a role in sugar translocation and the synthesis of cell wall material. Like Si, B can readily form complexes with polyhydroxy compounds. Hydroxyl groups of monosilicic acid like those in boric and phosphoric acids can condense with sugars, alcohols, and organic acids. This may indicate that Si can replace or interfere in the functioning of P or B. There is evidence that high Si/B ratios in the culture medium may restrict the growth and B uptake by the marine diatom *Cylindrotheca fusiformis* (Lewin, 1966).

Interaction with Nitrogen and Potassium

Plant leaves are generally more erect when the supply of Si is high and show a drooping habit when their Si content is low. Leaf erectness is one of the most important factors that affect light conditions in a plant canopy. While the degree of leaf erectness is varietal characteristic, it can

be changed greatly by Si and N nutrition (Yoshida et al., 1969). Nitrogen tends to make rice leaves more droopy while Si keeps them more erect. Leaf erectness is well correlated with the light extinction coefficient of rice populations.

Wallace et al. (1976) observed that added N always decreased plant Si content. Silicon appeared to compete with nitrate for entry into plants. An increase in the Si/N ratio in the nutrient solution appeared to increase the tolerance of rice to salinity (Aoki and Ishikawa, 1971). Percent N in the whole third leaf of sugarcane at harvest decreased from 1.81 to 1.63 (insignificant) when Si concentration in pure nutrient solution was raised from 0 to 200 ppm (Wong You Cheong et al., 1973). Percent Si in the same tissue increased from 0.03 to 1.24.

The effects of Si accumulation on the contents of K in Si cells and adjacent cells of abaxial and adaxial epidermis of the leaf blade and sheath of rice were examined by electron probe analysis (Soni et al., 1972). Silicon accumulation in Si cells reduced the accumulation of K on both surfaces of the leaf blade and sheath. Grain and straw concentrations of P and K were increased by applying Si either alone or with Ca or Mg (Padmaja and Varghese, 1972). Application of Si to sugarcane in nutrient solution had no effect on leaf blade K (Wong You Cheong et al., 1973). Colloidal silica produced during the manufacture of Al salts increased the level of available K and P in sandy soils (Szafranek and Krauze, 1976).

Interactions with Microelements

The higher sugarcane and sugar yields often observed after Si applications were reported to be primarily the result of overcoming Mn toxicity in the plant tissues (Clements, 1965b). Correspondingly, by means of Si applications, yields of barley (Williams and Vlamis, 1957), oats (Vlamis and Williams, 1967), wheat (Vlamis and Williams, 1967), sudan grass (Bowen, 1972), bean (Horst and Marschner, 1978), rice (Okuda and Takahashi, 1962, 1965), sugarcane (Clements et al., 1967, 1974; Wong You Cheong et al., 1971a) and other crops were increased in culture media high in available Mn. The mechanism by which Si alleviates microelement toxicities of plants is still a matter of dispute. One main reason for the dispute is the strong inverse relation between the solubility of microelements and the pH of the culture medium.

Okuda and Takahashi (1965) showed that the effects of Si supply on alleviation of Mn and Fe toxicity in rice plants resulted from a decrease in Mn and Fe uptake by the plants. Mn^{2+} and Fe^{2+} are readily oxidized by rice roots and precipitated on root surfaces. Since the effect is greater in plants supplied with Si, it is assumed that Si promotes the oxidation power of rice roots with the resulting accumulation of Mn and Fe oxides on the root surface. Incidentally, Ponnamperuma (1964) had suggested that Si improved the oxygen supply to the root by increasing the volume and rigidity of the gas channels in the root and shoot of rice.

However, using ^{54}Mn, it was found that Si did not appreciably inhibit the uptake of Mn, but rather affected its micro-distribution in barley leaves (Williams and Vlamis, 1957). Cadmium uptake by rice was reported to be reduced by 80% by a basal dressing of calcium silicate plus fused magnesium phosphate (9% Si) (Takijima and Katsumi, 1973).

Vlamis and Williams (1967) tested six species of grasses for response to Mn covering a range from deficiency (up to 0.1 to 0.2 ppm Mn) to toxicity (5 ppm Mn) in nutrient solutions in the presence or absence of Si. They reported that the addition of 10 ppm Si to the nutrient solution prevented the appearance of Mn toxicity symptoms. In all grasses the effect of Si was to lower the Mn concentration, but it was concluded that this could be explained as a dilution effect due to the increased growth associated with Si addition. Bowen (1972) reported that one function of Si was the amelioration of Mn toxicity as manifested by increased dry matter accumulation by the Mn-sensitive plants when Si was added.

Clements and his co-workers (Clements, 1965b; Clements et al., 1967, 1974), studying the causes of sugarcane leaf freckling, stated that "once the Mn, Fe, and Al get into the leaves, if they do not encounter certain minimum levels of SiO_2 and/or Ca, they localize in such concentrations that they cause necrosis." Applications of calcium silicate have been found to decrease concentrations of Mn, Fe and Al in sugarcane leaves. Fox et al. (1967a) observed necrotic

spottings on sugarcane in areas where the Mn levels of the plant were low in comparison to Clements' standards. They concluded that Mn toxicity or an unbalanced Mn/Si ratio was not the only explanation for the necrotic spottings.

Horst and Marschner (1978) reported that bean plants tolerated high levels of Mn (up to 10^{-2} mM Mn) in nutrient solutions containing 10 ppm Si. This Mn tolerance was not caused by a depressing effect of Si on uptake or translocation of Mn but rather by an increase in the Mn tolerance of the leaf tissue. In the absence of Si, 100 ppm Mn in the leaf tissue was toxic, whereas with the supply of 40 ppm Si, up to 1000 ppm Mn in the bean leaf was not toxic. A molar ratio Si:Mn of 6 within the leaf tissue is sufficient to prevent Mn toxicity. The increase in Mn tolerance of bean leaves by Si seems to be primarily caused by the prevention of local Mn accumulation within the leaf tissue.

Samuels and Alexander (1968) showed that the addition of Si reduced the Mn level in sugarcane tissue but that might have been due to pH alterations rather than to other properties of Si.

In Florida, Gascho and Andreis (1974) reported no effect on the concentrations of Mn, Fe, Cu and Zn in sugarcane leaves by Si applications, although leaf freckling was reduced and sugarcane and sugar yields were increased. In a recent investigation, Gascho (1978) eliminated Mn or Cu as causative agents of sugarcane response to calcium silicate slag or sodium metasilicate. Wong You Cheong et al. (1971a)

indicated that the leaf malady they observed on sugarcane was not a result of toxic levels of Mn or Fe but rather a Si deficiency symptom.

The increase in tolerance of plant species to Mn and other heavy metals, by Si applications, seems to be primarily due to an increase in tissue tolerance as a result of a more homogenous distribution of the metals within the leaf tissue, thus preventing local accumulation in certain areas.

Resistance to Insects and Diseases

Application of silicate materials has been reported to increase the resistance of many crop plants to insect and disease damage. Raleigh (1939) noticed that beet plants grown in culture solution free of Si were more susceptible to damping off disease. Wagner (1940) reported that an adequate Si content might increase the resistance of some cereals to powdery mildew (*Erysiphe graminsis*). Several Japanese workers reported Si as adding to the resistance of rice to several diseases, namely blast (*Pyricularia oryzae*), brown spot (*Helminthosporium oryzae*), stem rot (*Leptosphaeria salvinii* Catt.) and sesame spot (*Cercospora sesami*). Applications of silicate materials reduced the incidence of rice blast while N and P rendered the plant more susceptible (Paik, 1975). Silicate materials were also effective in reducing the number of lesions of panicle blight of rice caused by *Cochliobolus miyabeanus* (Watanabe et al., 1976).

Tamimi and Hunter (1970) reported that application of TVA slag together with P reduced the level of infection by corn smut (*Ustilago maydis*). Aoki and Ogawa (1977) observed that the severity of blossom-end rot of tomato was consistently associated with factors causing a low Si supply in the culture medium.

Silicon in plants is also related to their resistance to certain insect pests. Resistance of rice to stem borer (*Chilo suppressalis* (Wlk.)) (Djamin and Pathak, 1967), wheat to Hessian fly (*Mayetiola destructor* (Say)) (Miller et al., 1960) and sorghum to central shoot fly (*Atherigone indica*) had been found to increase with increasing concentration of Si in the plant. Resistance in some rice strains to first-instar larvae of *Tryporyza incertulas* (Walker) is related to high contents of Si (Subbarao and Perrajn, 1976). Application of 3% KCl to sugarcane foliage decreased leaf Si and lowered the plant's resistance to the shoot borer *Chilo infuscatellus* (Sithanantham et al., 1976). Analysis of leaf sheaths of three sugarcane varieties revealed that resistance to the sheath mite *Aceria sacchari* was positively associated with Si content (Sithanantham and Srinivasan, 1975).

The way in which Si in plants increases resistance to insects and diseases is mainly mechanical. Silicon in plant cell walls may constitute a mechanical barrier to penetration either by fungal hyphae or by mandibles of insect larvae. Resistance of rice to the stem borer *Chilo suppressalis* was determined by observing the condition of mandibles and tracing

feeding residue and excrement (Maxwell et al., 1972). The mandibles of the insect larvae which fed on silicated rice plants were diminished remarkably; thus it seemed that the silicated rice stem became too hard for the larvae to eat. Yoshida et al. (1959) hypothesized that polymerized silicic acids in rice filled up apertures of cellulose micelle constituting cell walls and made up a silicocellulose membrane which protected the plant from insect and fungal attack. Silicon in plants tends to deposit as silica gel under the leaf cuticle forming the so-called "cuticle-silica double layer" (Yoshida et al., 1962). The presence of this layer may well explain why increased absorption of Si increases the resistance of rice plants to insects and diseases and suppresses transpiration (Ishizuka, 1971). Silicon may protect plants in another way. Its combination with one or more components of the cell wall is likely to make cell walls more resistant to the enzymatic degradation which accompanies the penetration of cell walls by fungal hyphae.

Leaf Disposition and Photosynthetic Efficiency

Rice leaves are more erect when the supply of Si is hi and show a drooping habit when their Si content is low. Ishizuka (1971) showed that a difference of leaf angle alone could account for differences in canopy photosynthesis of 10-40%. This effect is usually obtained at high N levels and its magnitude on grain yield is about 10%. In the tropics, rice growth tends to become excessive, and mutual shading is often the cause of low grain yields. In such an

environment, leaf erectness may assume greater importance than it does under temperate conditions. Silicon applications increase leaf thickness (Yoshida et al., 1969) and light transmission (Kwon et al., 1971) by rice stands. Silicon application also increases the number of silica cells in sugarcane leaves (Lau et al., 1978). These cells act as "windows" through which light can pass resulting in more efficient light utilization.

Water Economy of Plants

Silicon may play some important role in regulating the rate of transpiration, probably cuticular transpiration, and thereby contribute to better growth of plants particularly under conditions of low humidity (Tanaka and Park, 1966). The rate of transpiration of Si-deficient rice plants is 30% higher than the rate of control plants (Yoshida et al., 1959). Okuda and Takahashi (1965) reported that the transpiration rate of rice plants was decreased from 5.1 to 3.6 ml/g fresh weight/24 hours when the supply of Si was increased from 0 to 47 ppm in the culture solution. An increased rate of transpiration in Si-deficient plants could explain the wilting that might occur and the increased accumulation of microelements in the aerial part of plants. The rate of transpiration may be influenced by the amount of silica gel associated with cellulose in cell walls of epidermal cells. The presence of the "cuticle-silica double layer" mentioned earlier may enhance the efficiency of the cuticle to suppress the rate of transpiration.

Other Response Mechanisms

Application of silicate materials to low Si culture media may benefit plants in many additional ways. Lodging of cereals results in considerable loss of yield. This phenomenon is generally associated with high levels of N and unlimiting soil moisture which give rise to the formation of long, weak, lower internodes which bend easily. Silicon significantly decreases the length and breadth of the stem vascular bundles and results in the production of thick-walled compact cells which increase lodging resistance of plants (Chandramony and George, 1976).

Silicon also ameliorates the growth retarding effects of high or low temperatures (Okamoto, 1969), increases the oxidizing power of rice roots (Okuda and Takahashi, 1965) and increases photophosphorylation in both leaves and roots of sugarcane (Wong You Cheong et al., 1971b). Although it has been reported that Si inhibits the action of invertase in sugarcane (Alexander, 1968, 1969), such inhibition results from increase of pH of the medium rather than from the effect of Si per se (Wong You Cheong et al, 1971b). Silicon promotes head sprouting of rice and may play an important role in determining the fertility of rice plants (Mitsui and Takatoh, 1963). Nishihara et al. (1978) reported that plant height, spikelets/ear, tillers, grain weight and percent of fully ripened grain were reduced in Si-deficient rice plants. A high Si content of the glumes of canary grass *Phalaris tuberosa* L. is one of

several characteristics associated with high seed retention (McWilliams, 1963). This indicates that Si fertilization may help to reduce seed shattering which is common in grasses, sesame and other crop plants. Plucknett (1971) summarized the effects of Si on sugarcane as follows: (1) correction of leaf freckling, (2) larger growth index, (3) longer stalks with larger diameters, (4) larger suckers, (5) increased number of green and functioning leaves, (6) more cane and dry matter yields, and (7) higher sucrose yield.

Ultraviolet Light Effects on Plants

The spectrum of the ultraviolet portion of light ranges between 200 nm, or less, and 400 nm. The general biological divisions of this spectrum are: (1) "black light" or UV-A (400-320 nm), (2) erythmal region or UV-B (320-280 nm), (3) germicidal region or UV-C (280-200 nm), and (4) Schuman region or extreme UV (less than 200 nm) (Lockhart and Brodführer, 1961). The solar UV irradiation reaching the earth's surface consists mainly of UV-A and UV-B. The energy flux density decreases sharply from 400 nm to 280 nm. More than 90% of the total energy in the terrestrial solar UV spectrum is of the UV-A type, but this energy is not as effective as UV-B in alterning photochemical responses of plants (Caldwell, 1971). Terrestrial UV flux densities increase with increasing latitude and vary considerably with

season (Cutchis, 1974). The short wavelengths of the UV spectrum contain the highest energy per quantum, and large doses of these wavelengths are detrimental to both plants and animals (NAS, 1973; Lockhart and Brodführer, 1961). Some of the effects include skin cancers, inhibition of photosynthesis, reduction of plant growth, and death of some plants (Crutzen, 1974).

The lethal shorter wavelength UV radiation (UV-C and portions of UV-B) is absorbed by the ozone layer found in the stratosphere (10-50 kilometers above sea level). Although the total amount of ozone (O_3) in the stratosphere is very small (Thrush, 1977), its presence is essential for life on this planet. If the present ozone level decreased to half its amount, the cut-off wavelength of UV radiation would be reduced from 298 nm to 290 nm which is closer to the wavelength region of maximum absorption of UV radiation by DNA and proteins (Crutzen, 1974). The shielding of these vital compounds from the harmful UV radiation by ozone is indispensable for life.

The present ozone level in the stratosphere is subject to breakdown and depletion by several human activities in advanced societies as well as by natural causes. These include nuclear explosions (Hammond and Maugh III, 1974; NAS, 1975; Koslow, 1977); nitrogen oxides released directly into the stratosphere by supersonic aircraft (Johnson, 1971; Cutchis, 1974; Crutzen, 1974; Alyea et al., 1974; Hammond,

1975); release of chlorofluoromethanes in the atmosphere through the use of Freon I and Freon II as refrigerants, propellants in spray cans, and in foam blowing (Cicerone et al., 1974; Crutzen, 1974; Hammond and Maugh III, 1974; Molina and Rowland, 1974; Hammond, 1975; Wofsy et al., 1975); greatly increased use of nitrate fertilizers (Crutzen, 1974; Keeney, 1978; Guse, 1978); natural agents as volcanic activities, high thunderheads, and intense tropospheric circulation patterns including cyclones and hurricanes. These agents are sources of pollutants which catalyze the destruction of the ozone layer in the stratosphere. The depletion of the mean global amount of ozone by these agents has been estimated to reach up to 50 percent (Crutzen, 1974). This would be accompanied by increases in UV-B photon flux densities which might be lethal to plants and animals.

During the past 80 years a considerable amount of research has been conducted on responses of higher plants to UV radiation. However, relatively little work has been devoted to the investigation of the effects of UV-B radiation on plants (Lockhart and Brodführer, 1961; Caldwell, 1971; Berg and Garrard, 1976; Sission and Caldwell, 1976; Van et al., 1976; Brandle et al., 1977). The effects of UV-B radiation on plants have been studied using irradiance regimes simulating a 50 percent stratospheric ozone depletion. Most studies with artificial light sources have been conducted with quartz mercury vapor lamps (Caldwell, 1971; Biggs, 1974), type FS-40 Westinghouse fluorescent sun lamps (Berg III,

1975), and type BZ fluorescent lamps (Kessler, 1977). Different filtering devices have been used to simulate expected UV-B increases (Carns et al., 1977). These include Mylar which cuts off at 315 nm, cellulose acetate (CA) at 290 nm, polystyrene at 285 nm, and pyrex glass which transmits wavelength above 275 nm.

How UV-B Radiation Affects Plants

The impact of increased UV-B radiation (280-315 nm) on growth and productivity of plants is substantial. UV-B damage may range from significant changes in dry matter production to subtle changes in photosynthesis, pigmentation, nutrient transport, abscission, as well as other anatomical and biochemical changes (Biggs and Basiouny, 1975). UV-B damage under field conditions is generally less than the damage caused by artificial UV-B in growth chambers or greenhouse (Hart et al., 1975) because of the available visible light (400-700 nm) for photorepair and the great biological variability. The initial response of UV-B radiation damage is destruction of leaf epidermal layers, followed by destruction of successive tissue layers through the palisade into the spongy mesophyll until the leaf is completely desiccated (Carns et al., 1977).

The UV irradiance in the UV-B range can be increased for experimental purposes by an amount corresponding to about 50 percent decrease in ozone. The UV supplementation can be achieved by use of sunlamps whose light is filtered through

thin cellulose acetate films (5 mil* in diameter) so as to cut out wavelengths below 290 nm. Control plants are exposed through thin Mylar films that cut out wavelengths below 310 nm. Thus Mylar transmits supplementary UV-A (310-400 nm) while cellulose acetate transmits UV-B plus UV-A (290-400 nm).

Enhanced UV-B radiation has been reported to decrease dry weight per plant of many crops (Lockhart and Brodführer, 1961; Caldwell, 1968, 1971). Thai and Garrard (1975) found a significant decrease in fresh and dry weight of soybean grown in a greenhouse under UV-B radiation. However, Hart et al. (1975) reported no effect on different UV-B radiation intensities on dry weight of soybean grown both under field and greenhouse conditions. In an attempt to study UV-induced ultrastructural changes in mesophyll cells, Campbell (1975) reported that soybean mesophyll cells which had been irradiated with UV-B showed enhanced senescence. He attributed this to changes in membrane permeability. In studies with ^{65}Zn-labelled cotton-seed from Acala 442-77 and Gregg 45 cultivars, changes in ^{65}Zn translocation from the cotyledons were noted as a result of UV-B radiation of the germinated seeds (Ambler et al., 1975).

UV-B radiation induced anthocyanin formation in cotton (*Gossypium spp.* L) (Carns et al., 1977) and leaf freckling in sugarcane (Wong You Cheong, et al., 1971a). These

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*1 mil = 0.001" = 0.025 mm

phenomena was observed in plants grown in the field but not in the greenhouse. A Perspex or a glass roof in a greenhouse effectively prevented the penetration of UV-B radiant energy and sugarcane leaf freckling (Gascho, 1978; Wong You Cheong et al., 1971a).

Plants have evolved protective mechanisms to cope with the damaging UV-B radiation. These include cuticular and epidermal "pigments" which absorb 280-320 nm radiation, photorepair by low energy radiation, presence of sooty molds on leaf surfaces, division of labor such that UV-B sensitive reactions occur at night (Biggs and Basiouny, 1975), positional movements or organs and subcellular particles, and induced morphological changes (Biggs and Basiouny, 1975).

CHAPTER 3

MATERIALS AND METHODS

UV-B Irradiance Greenhouse Experiment

The soil used in this investigation was Pahokee muck (Typic Medisaprist) collected from a virgin land two miles south of the Agricultural Research and Educational Center, Belle Glade (AREC). The soil was sieved with a 10-mesh U.S. sieve and left overnight to dry. After being thoroughly mixed, the soil was sampled for chemical analysis and moisture determination (Table 1). The soil was then steam sterilized and mixed with an equal volume of acid-washed sand.

Sugarcane (a complex trispecies hybrid of *Saccharum*), variety C.P. 63-588, was used in the study. One-eye seedpieces were waxed from both sides to prevent fungal infection and were planted upright in galvanized zinc flats on 15 July 1978. The seedpieces were watered daily with deionized water. Uniform seedlings were transplanted into 40-liter galvanized zinc pots on 9 August 1978. Four seedlings were transplanted into each pot. The pots were immediately watered with deionized water to wet the whole profile. The seedlings were watered with deionized water every other day until the rate of evapotranspiration increased to the point where they had to be watered daily.

Table 1. Chemical analysis of Pahokee muck soil

Soil type	pH[+]	Si[‡]	P[‡]	K[++]	Ca[++]	Mg[++]	Moisture
		ppm	-------Kg/ha--------				----%---
Pahokee muck	4.8	8	26	57	3960	482	46

[+] 2:1 water:soil suspension

[‡] Water-extractable

[++] 0.5 M acetic acid-extractable

The seedlings were allowed to grow inside the greenhouse under supplemental UV-B irradiance provided by 111-cm 40-W Westinghouse FS-40 fluorescent sun lamps mounted in 122-cm fixtures and filtered with 0.127-mm (5 mil) layers of UV-B transmitting cellulose acetate (CA). The experimental area was divided into four compartments with a 0.127-mm (5 mil) film of UV-B absorbing Mylar S filter. Control conditions also were provided by filtering the lamps with Mylar S. Both CA and Mylar S transmit more than 85% of the photosynthetically active radiation of the spectrum (PAR 400-700 nm). However, CA and Mylar S transmission cut-off is reduced to 1% at about 292 and 316 nm, respectively (Vu et al., 1979). Each of the four compartments was provided with four fixtures, two in a row, and two sun lamps were mounted in each fixture. The fixtures were provided with steel reflectors covered with aluminum foil to increase the UV-B irradiance reaching the plants. Radiation from the lamps was filtered either through CA (UV-B enhanced) or Mylar S (control). The UV-B irradiance

treatments were expressed in sunburn units (S.U./hour) and measured with a Solar Ultraviolet Meter Model SSI 7880 (Solar Light Co., Philadelphia). The treatments were 2, 3, and 4 S.U./hour and Mylar S control. The required sunburn unit reading for each UV-B treatment was obtained by adjusting the distance for lamps to plants using the Solar Ultraviolet Meter. The calibrated distances for the 2, 3, and 4 S.U./hour treatments were 52, 38, and 28 cm., respectively (Figure 1). The distance from lamps to plants in the control treatment was adjusted similar to the 3 S.U./hour treatment. The relation between sunburn units and UV-B irradiance and UV-B sun equivalent units ($UV\text{-}B_{seu}$) is shown in Figure 2. One $UV\text{-}B_{seu}$ equals 15.98 weighted mWatts m^{-2}, weighted by $EXP\text{-}[(\lambda\text{-}265)/21]^2$ from 280 to 340 nm. The light was put on daily for 6 hours from 1000 to 1600 EST. The lamp-to-plant distance for each UV-B treatment was adjusted daily with the Solar Ultraviolet Meter. Since the transmission of UV-B irradiance by CA is drastically reduced after 5 days, the filter was changed twice a week. Three Si treatments, each replicated 5 times, were imposed within each UV-B treatment. The Si treatments were 0, 68, and 136 g of sodium metasilicate ($Na_2SiO_3 \cdot 9H_2O$) per pot. One third of the Si treatment was applied on 22 August 1978, and the remaining two thirds were applied on 12 September, 1978.

A 20-20-20 soluble fertilizer concentrate (Nutri-Leaf 60), manufactured by Miller Chemical and Fertilizer Corporation, Hanover, Pennsylvania, was applied weekly with the

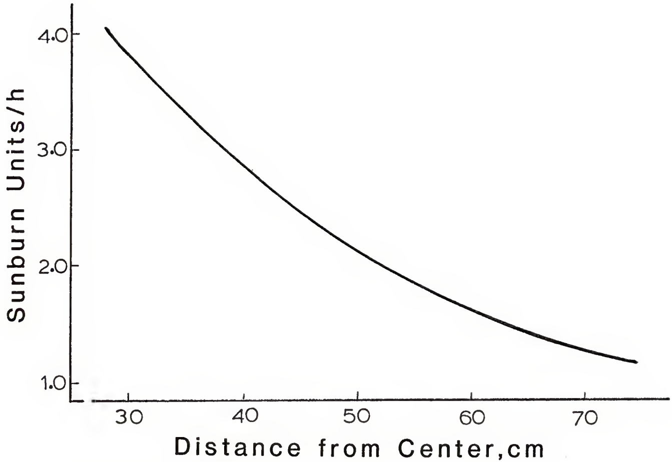

Figure 1. Sunburn units of 4 FS-40 sun lamps as a function of distance from a point directly under the lamps

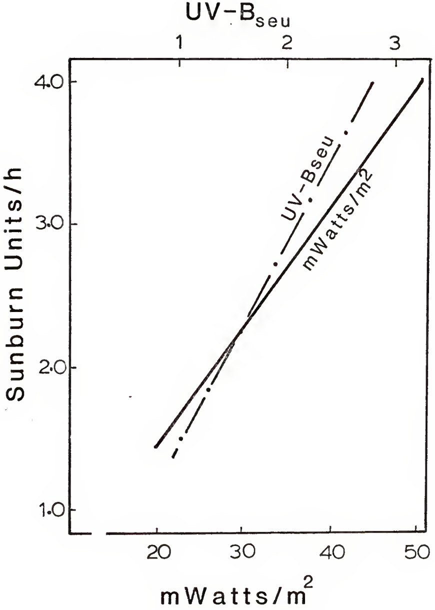

Figure 2. Relation between UV-B irradiance and UV-B sun equivalent units and sunburn units. (Adapted from Allen et al., 1978).

irrigation water, starting on 12 August. The amount applied was 1.7 g per pot per week.

Thimet 10G was applied to the soil at the rate of 0.5 g per pot (50 Kg/ha) to control wireworm (*Melanotus communis*) as well as other insect pests. Azodrin was applied to the foliage two weeks after transplanting at the rate of 15 g per gallon of water to control stem borers (*Diatraea saccharalis* (F)). The application of Azodrin was repeated the following day for effective control. Azodrin again was applied on 3 October and repeated on 4 October 1978.

The midday photosynthetically active radiation (PAR 400-700 nm) inside the greenhouse was about 900 $\mu E\ m^{-2}\ sec^{-1}$ above the sun lamp fixtures, 700 $\mu E\ m^{-2}\ sec^{-1}$ at plant height, and 200 $\mu E\ m^{-2}\ sec^{-1}$ at the soil surface. Outside the greenhouse the midday PAR was about 1300 $\mu E\ m^{-2}\ sec^{-1}$. Temperatures inside the greenhouse ranged from 22°C (nighttime) to 37°C (daytime). Outside the greenhouse temperatures ranged from 18°C to 25°C. Relative humidities fluctuated from 82% (nighttime) to 35% (daytime) inside the greenhouse and from 96% to 62% outside the greenhouse.

The experiment layout in the greenhouse was a nested design in which 4 UV-B irradiance treatments and 3 Si treatments were nested within pots. The 15 pots within each UV-B treatment were shuffled once a week. Two samples were collected from each pot. Sugarcane seedlings also were allowed to grow inside and outside the greenhouse without exposure to any lamps in another experiment. Completely

randomized design was used with three Si treatments and 5 replications. In both experiments, analyses of variance and least significant difference (LSD) were studied using Statistical Analysis System (SAS) procedures.

Plant and first ratoon crops were studied to investigate the effects of UV-B irradiance and Si on the growth and yield of sugarcane seedlings. Leaf samples (top visible dewlap leaf, TVD) and soil samples (0-30 cm) were taken on 9 December 1978 for the plant crop and on 10 April 1979 for the ratoon crop. Two samples were taken from each pot in the UV-B irradiance experiment. Leaf samples were placed in paper bags and dried at 70°C for 24 hours. The samples were ground in a stainless steel Wiley mill and analyzed for N, P, K, Ca, Mg, Fe, Mn, Zn, Cu, and Si. Soil samples were analyzed for pH (1:2 soil:water suspension), water-extractable Si and P, and 0.5M acetic acid-extractable K, Ca, and Mg.

Plant height (from soil surface to TVD), stem diameter (at 15 cm from soil surface), and leaf area (total leaf area of two plants) were measured on 10 December 1978 for the plant crop and 12 April 1979 for the ratoon crop. Plant and ratoon crops were harvested when they were each four months old (15 December 1978 and 15 April 1979, respectively). At harvest, plants were cut at soil surface, placed in paper bags, and dried at 70°C for 48 hours. The fresh and oven-dry weights of the samples (2 plants/sample) were expressed as fresh weight yield and dry-matter yield in g/pot, respectively.

Silicate Field Experiment

A field study was conducted in the Florida Everglades agricultural area during 1979-80 to compare the effects of calcium silicate slag from TVA, a similar slag produced in Florida, and Portland cement on the growth and yield of sugarcane. The materials were applied to a Pahokee muck soil at five rates in a randomized complete block design in plots within a commercial field. The rates were 0, 5, 10, 15, and 20 MT/ha of material. Table 2 shows the elemental analysis of the three silicate materials. Nutrient levels in the different silicate treatments are shown in Table 3. The treatments were replicated five times. Variety C.P. 63-588 was used for the study because it is the leading variety in Florida and because of its known response to calcium silicate applications. The experimental area consisted of 75 plots which covered an area of 0.6 ha. The materials were spread by hand on 15 November 1978. The following day the materials were turned over by a disc plow and the land was furrowed. The plots were planted 21 November 1978. Thimet 15-G was applied with the seed pieces in the furrow at the rate of 29 kg/ha to control wireworms as well as other insects. Fertilizer was applied on 31 October 1978 for the plant crop and consisted of 785 kg/ha of a 0-10-40 containing 0.48% Cu, 0.48% Zn, and 0.19% B. The same fertilizer (0-10-40) was applied to the ratoon crop at the rate of 450 kg/ha immediately after harvesting the plant crop.

Table 2. Elemental analysis of 3 silicate materials used in the silicate field experiment

Element	P	K	Ca	Mg	Si	Fe	Mn	Zn	Cu
	------	------	------	%	------	------	------	ppm	------
Material									
TVA+	0.27	0.30	18.25	0.67	16.4	0.43	869	25	10
Fla‡	0.54	0.02	15.75	0.30	24.4	1.44	188	12	15
Cement	0.00	0.02	25.17	0.54	8.2	1.63	200	205	12

+TVA slag, electric furnace slag from the manufacture of elemental P from the Tennessee Valley Authority.

‡Florida slag is similar to TVA slag but is produced in Florida.

Table 3. Nutrient levels in the different silicate treatments

Material	Rate	P	K	Ca	Mg	Si	Fe	Mn	Zn	Cu
	MT/ha	----------	----------	----------	----------	kg/ha	----------	----------	----------	----------
TVA slag	5	14	15	913	34	820	22	4	Trace+	Trace+
	10	28	30	1826	68	1640	44	8	"	"
	15	42	45	2739	102	2460	66	12	"	"
	20	56	60	3652	136	3280	88	16	"	"
Fla slag	5	28	1	788	15	1220	72	1	Trace+	Trace+
	10	56	2	1576	30	2440	144	2	"	"
	15	84	3	2354	40	3660	216	3	"	"
	20	112	4	3152	60	4880	288	4	"	"
Cement	5	0	1	1259	27	410	82	1	1	Trace+
	10	0	2	2518	54	820	164	2	2	"
	15	0	3	3777	81	1230	246	3	3	"
	20	0	4	5036	108	1640	328	4	4	"

+<1 Kg/ha

Effects of the different silicate materials were evaluated on the basis of number of millable stalks, stalk length and diameter, freckling percentage, chlorophyll content and nutrient concentrations in the TVD leaf blade, cane and sugar yields, and soil composition.

Number of Millable Stalks

Millable stalks (1000's/ha) were counted on 28 June 1979 and 22 June 1979 for plant and ratoon crops, respectively. The number of millable stalks per 6 m row was counted, then converted to number of millable stalks per ha.

Stalk Length and Diameter

Stalk length and diameter also were measured at the same time millable stalks were counted. Stalk length was measured from soil to TVD. Stalk diameter was measured at 30 cm above soil using a caliper and ruler.

Leaf Sampling

Leaf samples were taken three times a season for nutrient concentration, chlorophyll content, and freckling percentage determinations. The sample consisted of 20 TVD leaf blades minus the midrib. The leaf blades which showed sugarcane freckling were counted and freckling percentage was calculated. Then the sample was segregated into two groups, one for the study of nutrient concentration and the other for the study of chlorophyll content. The sample for nutrient concentration was put in a 70°C oven for 24 hours, ground in a stainless steel Wiley mill, and stored in small glass bottles. Subsamples were taken to determine the concentrations of Si, N, P, K, Ca, Mg, Fe, Mn, Zn, and Cu. The sample for chlorophyll content was ground fresh using a mortar and pestle and chlorophyll was extracted in 80% acetone (Yoshida et al., 1976).

Cane and Sugar Yields

Plant and ratoon crops were harvested in 5 December 1979 and 22 September 1980, respectively. Twenty random stalks were harvested in each plot. The stalks were stripped and their fresh weight was determined. Cane yield in metric tons

per ha were calculated. The cane was milled by a 3-roller mill. Sugarcane juice was clarified with lead subacetate and the pol reading was made on the cleared juice using a Bausch & Lomb Polarimeter with Lippich Polarizer. Brix reading was made on the uncleared juice using a Bausch & Lomb Refractometer. Using the pol reading and Brix, percent sucrose was determined from Table 36 in Spencer and Meade (1948). Percent yield 96° sugar was calculated and metric tons sugar/ha (TSH) were calculated.

Soil Sampling

Soil samples were taken with a soil probe on 25 June 1979 and 15 September 1980 for plant and ratoon crops, respectively. Ten cores were collected to a depth of 30 cm from each plot, and a composited sample was taken to the laboratory. Soil pH, water-extractable P, and 0.5 M acetic acid-extractable K, Ca, and Mg were determined according to methods as described by Thomas (1970). Water-extractable Si also was determined.

Statistical Procedures

Multiple regression analyses were run using SAS procedures. Both linear and quadratic models were run for each parameter. Regression equations were developed from the linear model unless the quadratic model was significant. The data reported in tables have R^2 values associated with the regression model used. The form of the independent variable in the multiple regression was $a + bx + cx^2 + dx^3 \ldots$. Analysis of variance was performed on the material sources. Means of the materials were separated by LSD.

CHAPTER 4

RESULTS AND DISCUSSION

UV-B Irradiance Greenhouse Experiment

The effects of UV-B irradiance and reagent grade sodium silicate ($Na_2SiO_3 \cdot 9H_2O$, 9.8% Si) application on plant height, stem diameter, leaf area, nutrient concentration, dry-matter yield, and soil composition will be discussed.

Growth and Dry Matter Yield

Plant height, stem diameter, leaf area, and dry-matter yield of both plant and ratoon crops of sugarcane plants increased significantly with increasing amount of sodium silicate (Table 4). The effectiveness of Na silicate was due mainly to its high solubility and strong alkalinity. The beneficial effect of the material, as reflected in growth and dry matter yield, could be attributed in part to increased levels of soil Si and soil pH (Table 9). Similar results have been reported by Alexander et al. (1972) and Gascho (1978). Clements (1980) indicated that field application of Na silicate increased metric tons pol/ha (TPH) but did not affect metric tons cane/ha (TCH).

Plant height, stem diameter, leaf area, and dry-matter yield of sugarcane plants exposed to supplemental UV-B

Table 4. Influence of Si and UV-B irradiance on growth and dry matter (D.M.) yield of sugarcane plants

Na_2SiO_3 + g/pot	Plant Crop				Ratoon Crop			
	Plant height	Stem diameter	Leaf area	D.M. yield	Plant height	Stem diameter	Leaf area	D.M. yield
	--------cm------		cm^2/ 2 plants	g/2 plants	---------cm--------		cm^2/ 2 plants	g/2 plants
0	134c	2.8c	10954c	367c	64c	1.6b	5960c	223c
68	159b	2.9b	11312b	400b	69b	1.8a	6630b	250b
136	171a	3.0a	11643a	430a	79a	1.8a	7228a	276a
UV-B irradiance (S.U./hr)‡								
0	155a	3.1a	11902a	424a	100a	1.7a	10620a	376a
2	143b	3.0a	11680b	407b	65b	1.7a	5236b	245b
3	129c	2.8b	11020c	405b	51c	1.7a	5044c	240b
4	120d	2.6c	10610d	361c	45d	1.6b	4832d	160c

+Means of 40 observations.

‡Means of 30 observations. Means in the same column followed by the same letter are not significantly different (LSD) at the 5% level of probability.

radiation are also presented in Table 4. Significant reductions in growth and dry-matter yield were measured for plants exposed to increasing levels of UV-B radiation. At the highest UV-B dose (4 S.U./hr), dry matter yields of plant and ratoon crops were reduced to 85 and 43% of the Mylar control, respectively. The ratoon crop appeared to suffer much more from the UV-B stress than the plant crop on basis of both growth and dry-matter yield. The higher the level of UV-B radiation, the greater was the inhibition in phytomass accumulation. Similar results were reported for soybean and corn under field (Caldwell et al., 1975) and greenhouse (Van et al., 1976; Vu et al., 1979) conditions. Thai and Garrard (1975) also reported a significant decrease in fresh and dry weight of greenhouse-grown soybean subjected to UV-B radiation.

Sugarcane plants exposed to enhanced UV-B irradiance inside the greenhouse showed no chlorotic or bronzing symptoms in their leaves. This militates against the hypothesis that UV-B radiation induces freckling in sugarcane leaves (Wong You Cheong et al., 1971a). Similar observations were reported for sweet corn (Vu et al., 1979). Enhanced UV-B irradiance, however, was reported to induce chlorotic and bronzing symptoms in leaves of cotton (Carns et al., 1977) and soybean and peas (Vu et al., 1979). Leaves of sugarcane and sweet corn seem to be more tolerant to UV-B damage than leaves of soybean and peas.

Sugarcane plants grown outside the greenhouse without Si showed leaf freckling symptoms although they were not exposed to supplemental UV-B irradiance. The maximum average reading indicated by the Solar Ultraviolet Meter at Belle Glade during the growth period of the plant crop (August to December, 1978) was 2.4 S.U./hr and it occurred at 1300 EST. Since UV-B damage outside the greenhouse is generally less than the damage caused by enhanced UV-B irradiance inside the greenhouse (Hart et al., 1975), leaf freckling of plants grown outside the greenhouse was caused by something other than solar UV-B light.

The effect of Na silicate on sugarcane plants grown outside the greenhouse is shown in Table 5. The striking difference between plants inside and outside the greenhouse was the ability of tillering. Plants grown outside the greenhouse produced more tillers especially when Na silicate was applied. On the other hand, plants grown inside the greenhouse did not tiller even with the top rate of Si because light was limiting. Under normal light conditions, silica (as $SiO_2 \cdot nH_2O$) deposited in silica cells and stomatal guard cells may serve as "windows," allowing more light to pass through the epidermal tissue to the photosynthetic mesophyll tissue (Lau et al., 1978), thus allowing for more tillers per plant.

On 2 October 1978 plants grown inside the greenhouse were attacked by stem borer (*Diatraea saccharalis* (F)). The total number of infested plants for each Si treatment is

Table 5. Influence of Si on plant number and fresh and dry weight of sugarcane plants (outside the greenhouse)

	Plant Crop			Ratoon Crop		
Na_2SiO_3 g/pot[+]	Plant no.	Fresh weight	Dry weight	Plant no.	Fresh weight	Dry weight
0	7c	1850c	450c	6c	1628c	408c
68	9b	1925b	482b	8b	1764b	460b
136	11a	2010a	505a	11a	1906a	483a

[+]Means of 5 observations. Means in the same column followed by the same letter are not significantly different (LSD) at the 5% level of probability.

shown in Table 6. Application of the silicate material protected plants against stem borer. Many investigators have reported that Si increased plant resistance to certain insect pests (Djamin and Pathak, 1967; Sithanantham and Srinivasan, 1975; Sithanantham et al., 1976).

Nutrient Concentration

The influence of Si and UV-B irradiance on nutrient concentration in the TVD leaf blade of plant and ratoon crops are shown in Tables 7 and 8, respectively. In both plant and ratoon crops, application of Na silicate significantly increased the concentrations of Si, K, and Ca. On the other hand, concentrations of N, P, Mg, Fe, Mn, and Zn were significantly reduced due to the application of the soluble silicate material. The concentration of Cu was significantly increased in the plant crop but there was no significant increase in the ratoon crop. The enhancement of plant Si was mainly related to the high solubility of the material while the increase in K and Ca was related to its strong alkalinity. The Na silicate functioned in the soil solution as well as within the plant. Plant uptake of Si was greatly enhanced due to increased level of soluble Si in the soil solution (Table 9). Phosphorus, Mg, Fe, Mn, and Zn concentrations in the leaf were reduced as a result of increased soil pH. Gascho (1978) reported similar results for

Table 6. Influence of Si on plant resistance to stem borer (*Diatraea saccharalis* (F))

Na_2SiO_3 g/pot	No. of plants attacked	Percent of total
0	44	73
68	12	20
136	4	7

Table 7. Influences of Si and UV-B irradiance on nutrient concentration in the TVD leaf of sugarcane plants (plant crop)

Na_2SiO_3 + g/pot	Si	N	P	K	Ca	Mg	Fe	Mn	Zn	Cu
	%						ppm			
0	0.29c	2.41a	.36a	.92c	.25c	.22a	93a	72a	53a	6c
68	1.39b	2.19b	.28b	1.10b	.28b	.20b	74b	55b	38b	9b
136	2.38a	2.08b	.27b	1.28a	.31a	.18c	62c	45c	32b	12a
UV-B irradiance (S.U./hr)++										
0	1.21c	2.24a	.30a	1.08a	.24c	.19b	72c	53b	40a	7c
2	1.15c	2.22a	.29a	1.09a	.26c	.18b	78ab	55b	41a	8bc
3	1.38b	2.20a	.30a	1.10a	.29b	.20b	81a	60a	41a	9ab
4	1.65a	2.23a	.31a	1.13a	.33a	.23a	75bc	61a	42a	10a

+Means of 40 observations.

++Means of 30 observations. Means in the same column followed by the same letter are not significantly different (LSD) at the 5% level of probability.

Table 8. Influences of Si and UV-B irradiance on nutrient concentration in the TVD leaf of sugarcane plants (ratoon crop)

Na_2SiO_3+ g/pot	Si	N	P	K	Ca	Mg	Fe	Mn	Zn	Cu
	-------	-------	-------	%	-------	-------	-------	------- ppm	-------	-------
0	.23c	2.46a	.38a	.84c	.28c	.26a	82a	64a	40a	4a
68	.98b	2.27b	.24b	1.05b	.31b	.24b	68b	46b	32b	6a
136	1.67a	2.14b	.24b	1.24a	.33a	.20c	54c	38c	29b	6a
UV-B irradiance (S.U./hr)++										
0	.89a	2.34a	.32a	1.00b	.26b	.21a	64b	40c	34a	4a
2	.83b	2.30a	.30a	1.02b	.27b	.20a	70a	46b	33a	4a
3	.92b	2.28a	.29a	1.04b	.29b	.20a	73a	52a	35a	4a
4	1.28a	2.36a	.30a	1.16a	.34a	.22a	68a	54a	34a	6a

+Means of 40 observations.

++Means of 30 observations. Means in the same column followed by the same letter are not significantly different (LSD) at the 5% level of probability.

Table 9. Influences of Si and UV-B irradiance on soil composition

Na_2SiO_3 + g/pot	Plant crop						Ratoon crop					
	pH	Si	P	K	Ca	Mg	pH	Si	P	K	Ca	Mg
		ppm	--------Kg/ha--------					ppm	--------Kg/ha-------			
0	4.5c	6c	42a	96c	1272c	261a	4.6c	5c	52a	104c	1442b	274a
68	5.1b	16b	35b	113b	1436b	225b	5.5b	10b	48b	126b	1638a	248b
136	5.5a	24a	28c	131a	1652a	198c	5.9a	12a	34c	138a	1722a	219c
UV-B irradiance (S.U./hr)++												
0	5.3a	12b	32c	103c	1487a	238a	5.4a	10a	48b	113b	1456a	255a
2	5.4a	15a	34b	108c	1490a	241a	5.4a	10a	50b	109b	1460a	248b
3	5.3a	17a	37a	121b	1454a	222b	5.5a	11a	54a	130a	1420a	215c
4	5.3a	16a	38a	132a	1461a	227b	5.5a	13a	56a	134a	1446a	219c

+Means of 40 observations.

++Means of 30 observations. Means in the same column followed by the same letter are not significantly different (LSD) at the 5% level of probability.

P and Mn in above-ground plant parts when Na silicate was mixed with organic soils. Incorporation of soluble silicates with soils low in Si precipitates or blocks toxic materials in the soil solution or at exposed positions on soil surfaces. Severe cases of Mg, Mn, and Fe deficiencies may develop when localized piles of silicate materials are left behind. The decrease in P concentration due to the application of soluble Si contradicts the theory that application of soluble silicates solubilizes soil P (Tuilin, 1936; Toth, 1939; Cooke, 1956; Raupach and Piper, 1959; Teranishi, 1968; Roy et al., 1971) and improves P nutrition of the plant (Silva, 1971). The increase in Cu concentration was attributed to the possible contamination of Na silicate with Cu or to unknown soil reactions. Gascho (1978) reported similar results.

Supplemental UV-B irradiance resulted in increased concentrations of Si, Ca, Mg, Mn, and Cu in sugarcane leaves (Tables 7 and 8). Plant Si was increased from 1.21 and 1.65% and from 0.89 to 1.28% when 4 S.U./hr were applied to the plant and ratoon crops, respectively. Plant Ca also was increased in both plant and ratoon crops. The increase in elemental concentrations could be related to suppressed growth caused by UV-B irradiance (Table 4).

Soil Composition

Soil pH, Si, K, and Ca were increased due to the application of Na silicate, while soil P and Mg were reduced in both plants and ratoon crops (Table 9). Soil pH was increased

from 4.5 to 5.5 in the plant crop, and from 4.6 to 5.9 in the ratoon crop when the high Si rate was applied. This was explained by the high alkalinity of Na silicate. Soil Si quadrupled in the plant crop and more than doubled in the ratoon crop when the high rate of Si was applied. This was related to the high solubility of the material. Soil K and Ca were enhanced and soil P and Mg were reduced due to increased soil pH. Gascho (1978) reported similar results for soil Si, P, and Ca. Soil Ca was inversely related to soil P due to Ca fixation of phosphates in organic soils.

Supplemental UV-B irradiance resulted in increased soil Si, P, and K, reduced soil Mg, and had no effect on soil Ca and pH. Enhancement of soil Si, P, and K may be related to the reduced growth of plants receiving high doses of UV-B irradiance.

Silicate Field Experiment

The influence of different rates of TVA slag, Fla slag, and cement on growth and yield of sugarcane and soil composition will be discussed.

Number of Millable Stalks

Application of silicate materials to organic soils significantly increased the number of millable stalks per ha. Although there was no difference among the three silicate materials in the plant crop (Table 10), application of Fla slag resulted in more plants per area than TVA slag or cement in the ratoon crop (Table 11). Apparently application of the silicate materials increased the photosynthetic efficiency

Table 10. Influences of rate and type of soluble silicates on growth and cane and sugar yields of sugarcane+ (plant crop)

Silicate material‡	Millable stalks (10^3/ha)	Plant height cm.	Stem diam. cm.	Chl. content mg./g.	Freck-ling %	Tons cane per ha (TCH)	Sugar %	Tons sugar per ha (TSH)
TVA	112.2a	127.5a	2.88b	2.8a	39a	134a	9.7a	13.0a
Fla	115.0a	128.3a	2.86b	3.1a	48a	141a	9.9a	13.9a
Cement	110.2a	126.9a	2.97a	2.9a	45a	136a	10.2a	13.9a
Rate++ (t/ha)								
0	89.1**	112.1**	2.62**	1.8**	77**	93**	9.9	9.2**
5	106.7	127.5	2.84	2.9	51	126	9.8	12.3
10	114.2	131.1	2.91	3.0	41	144	9.8	14.0
15	121.3	131.8	3.04	3.2	31	156	10.0	15.6
20	131.1	135.4	3.10	3.7	19	167	10.0	16.6
R^2	0.62	0.78	0.71	0.73	0.66	0.70	0.30	0.67

+Growth parameters were measured in June, 1979, and harvesting was done in December, 1979.

‡Means of 25 observations. Means in the same column followed by the same letter are not significantly different (LSD) at the 5% level of probability.

++Means of 15 observations.

**Regression is significant at 0.01.

Table 11. Influences of rate and type of soluble silicate on growth and cane and sugar yields of sugarcane+ (ratoon crop)

Silicate material‡	Millable stalks (10^3/ha)	Plant height (cm.)	Stem diam. cm.	Tons cane per ha (TCH)	Sugar %	Tons sugar per ha (TSH)
TVA	82.3b	149.1b	2.45b	95c	7.7a	7.3c
Fla	89.8a	156.0a	2.53a	112a	7.8a	8.8a
Cement	84.4b	151.1b	2.52a	105b	7.7a	8.1b
Rate++ (t/ha)						
0	66.4**	111.3**	2.09**	63**	7.72	4.8**
5	84.8	148.9	2.53	99	7.74	7.6
10	93.9	163.7	2.63	126	7.80	9.9
15	105.5	173.1	2.71	142	7.72	11.0
20	76.8	165.5	2.55	89	7.64	6.8
R^2	0.75	0.96	0.93	0.80	0.24	0.77

+Sampling for growth parameters was done in June, 1980, and harvesting was done in September, 1980.

‡Means of 25 observations. Means in the same column followed by the same letter are not significantly different (LSD) at the 5% level of probability.

**Regression is significant at 0.01.

and the tillering ability of the crop. Silicon increases light transmission by rice (Kwon et al., 1971) and sugarcane (Lau et al., 1978) stands. Clements et al. (1974) reported that Si application increased the number of green leaves and reduced the number of freckled leaves of sugarcane plants, thus resulting in more efficient photosynthesis. Gascho (1978) reported a 12 and a 50% increase in number of plants per pot when an equivalent of 22 MT/ha of TVA slag and Na silicate was applied, respectively, to a pot experiment outside the greenhouse. Nevertheless, the increase produced by TVA slag was not significant. In this study, stalk number increased steadily with all levels of silicate materials in the plant crop. However, in the ratoon crop maximum stalk number was obtained at 12 MT/ha material, beyond which it was drastically reduced (Figure 3). This was attributed to unfavorable soil reactions (see p. 103).

Plant Height and Stem Diameter

Application of silicate materials significantly increased plant height and stem diameter of sugarcane plants. There was no difference in plant height among the three silicate materials in the plant crop (Table 10); however, Fla slag increased plant height significantly higher than TVA slag and cement in the ratoon crop (Figure 4). This was attributed to the higher levels of Si and/or P in Fla slag as compared to TVA slag and cement (Table 2). Cement increased stem diameter more than the two slags in the plant crop (Figure 5). In the ratoon crop Fla slag and cement

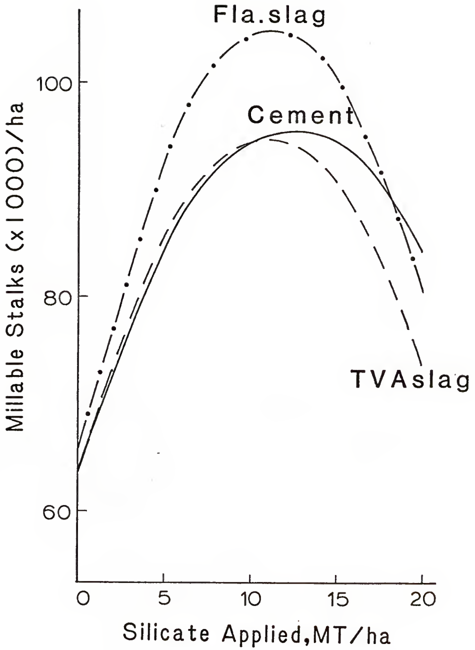

Figure 3. Influence of different rates of 3 soluble silicates on number of millable stalks (ratoon crop)

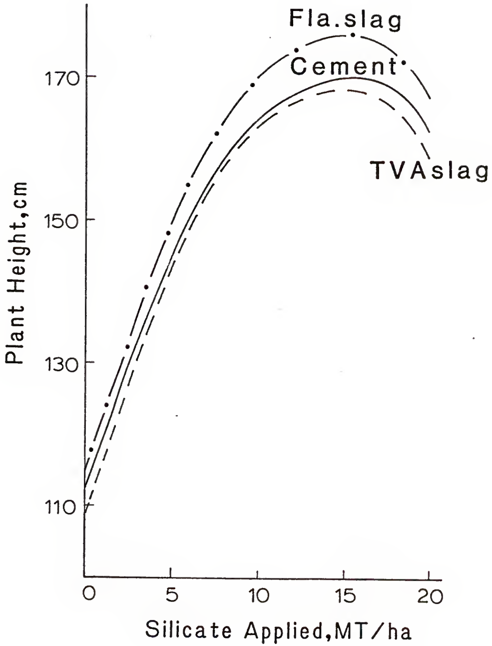

Figure 4. Influence of different rates of 3 soluble silicates on plant height (ratoon crop)

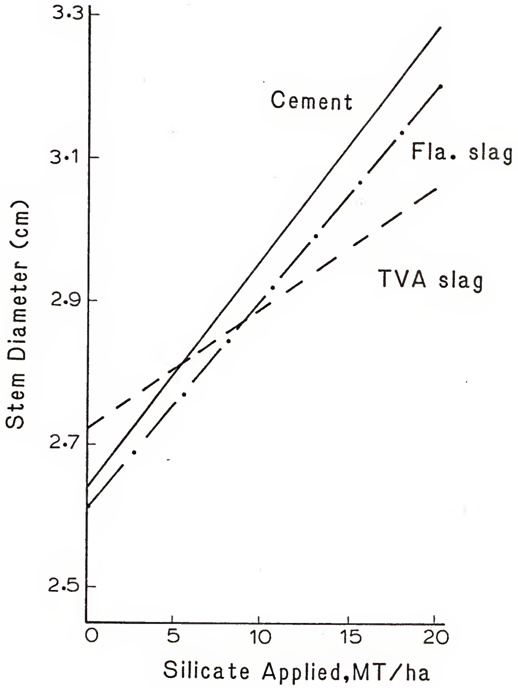

Figure 5. Influence of different rates of soluble silicates on stem diameter (plant crop)

increased stem diameter more than TVA slag (Figure 6). Maximum stem diameter was obtained with 12 MT/ha of either Fla or TVA slag and with 15 MT/ha of cement, then it dropped. This was caused in part by unfavorable soil pH. Since plants with long and large internodes weigh more and store more sucrose, then Fla slag may result in higher TCH and TSH than the other two materials. However, TCH and TSH depend not only on plant size but also on plant number. Gascho (1978) reported that addition of TVA slag and Na silicate resulted in long stalks. Nishihara et al. (1970) showed that plant height was reduced in Si-deficient rice plants. Plucknett (1971) indicated that some of the effects of Si on sugarcane were longer stalks with larger diameters and larger suckers. Silicon may be involved in cell elongation and/or cell division.

Chlorophyll Content and Percent Freckling

Chlorophyll content of the TVD leaf blade was more than doubled (Figure 7), and percent freckling was reduced from 77 to 19 when 20 MT/ha of soluble silicates was applied (Table 10). The correlation between chlorophyll content and percent freckling was negative and very strong ($r=-0.81$). There was no difference among the three silicate materials in chlorophyll content or percent freckling. Sugarcane leaf freckling has been reported in low Si soils by many investigators (Clements et al., 1974; Gascho, 1977, 1978; Gascho and Andreis, 1974; Wong You Cheong et al., 1971a). The

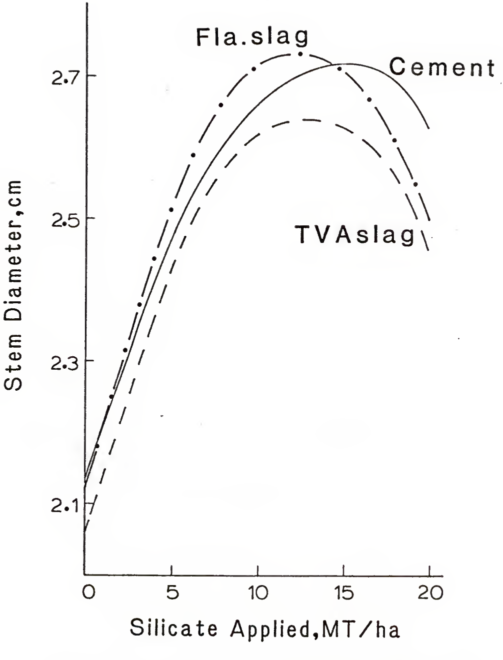

Figure 6. Influence of different rates of 3 soluble silicates on stem diameter (ratoon crop)

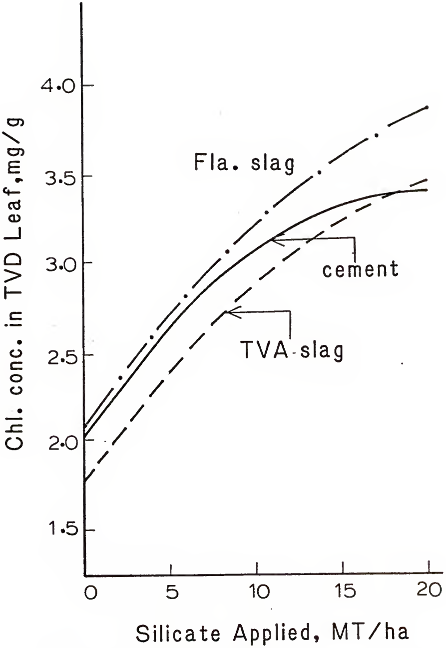

Figure 7. Influence of different rates of 3 soluble silicates on chlorophyll content in the TVD leaf; on fresh weight basis

cause of the malady is still a controversy. Clements et al. (1974) attributed leaf freckling of sugarcane to the presence of toxic ions in the soil solution and to high levels of Mn in the leaf sheath. Wong You Cheong et al. (1971a) concluded that leaf freckling was the foliar symptom of Si deficiency in the sugarcane plant. They also suggested that UV-B radiation from the sun might be necessary for the development of the symptom. In Florida, Gascho (1978) reported that leaf freckling of sugarcane was a symptom of the need for Si. Sugarcane leaf freckling was highly correlated with the amount of Si applied irrespective of the type of the silicate material (Table 12). It also was highly correlated with Si, Ca, Fe, Mn, Zn, and Cu in the TVD leaf. It was interesting to note that percent freckling was more correlated with plant Ca than with plant Si. However, chlorophyll content was more correlated with plant Si than with plant Ca. Plant data suggested that sugarcane freckling was caused by low levels of Si, Ca, and Cu and high levels of Fe, Mn, and Zn in the leaf. Application of silicate materials enhanced the levels of Si, Ca, and Cu and reduced the levels of Fe, Mn, and Zn in the leaf as will be discussed in the next section.

Nutrient Concentration

Influences of rate and type of silicate materials on nutrient concentrations in sugarcane leaf blades are shown in Tables 13-16.

Table 12. Correlation coefficients among some plant parameters

Plant Parameter	Freckling %	Chlorophyll content
Silicate material	0.09	.07
Rate	-.75	.80
Si	-.64	.78
Ca	-.67	.66
Fe	.52	-.59
Mn	.60	-.67
Zn	.61	-.66
Cu	-.56	.62
Freckling %	1.00	-.81

Table 13. Influences of rate and type of soluble silicates on nutrient concentration in sugarcane leaves[+] (June, 1979, sampling)

Silicate material[‡]	Si	N	P	K	Ca	Mg	Fe	Mn	Zn	Cu
	---	---	---	%	---	---	---	ppm	---	---
TVA	1.34b	2.21a	0.25b	1.34a	0.30b	0.18a	78a	56a	28a	7.2a
Fla	1.52a	2.14b	0.28a	1.32a	0.31b	0.21a	77a	52a	28a	7.4a
Cement	1.24b	2.18ab	0.20c	1.33a	0.33a	0.20a	76a	55a	29a	5.8b
Rate[++] (t/ha)										
0	0.82**	2.31**	0.21**	1.58**	0.24**	0.20*	92**	75**	34*	4.8**
5	1.28	2.23	0.24	1.41	0.28	0.21	86	58b	29	5.9
10	1.50	2.15	0.24	1.28	0.31	0.18	84	47b	27	6.5
15	1.61	2.14	0.25	1.20	0.34	0.18	68	41c	25	7.9
20	1.62	2.05	0.26	1.17	0.39	0.16	60	37c	25	8.8
R^2	0.92	0.75	0.81	0.72	0.75	0.51	0.62	0.70	0.61	0.77

[+]Means are expressed as percent or ppm of dry weight of TVD leaf minus midrib.

[‡]Means of 25 observations. Means in the same column followed by the same letter are not significantly different (LSD) at the 5% level of probability.

[++]Means of 15 observations.

*Regression is significant at 0.05.

**Regression is significant at 0.01.

Table 14. Influences of rate and type of soluble silicates on nutrient concentration in sugarcane leaves[+] (August, 1979, sampling)

Silicate material[‡]	Si	N	P	K	Ca	Mg	Fe	Mn	Zn	Cu
	%						ppm			
TVA	0.81a	2.07b	0.21a	0.89a	0.31a	0.18a	87a	90a	20a	4.8a
Fla	0.83a	2.16a	0.21a	0.92a	0.29b	0.17a	88a	68b	20a	4.8a
Cement	0.82a	2.11ab	0.21a	0.92a	0.32a	0.17a	83a	69b	19a	5.1a
Rate[++] (t/ha)										
0	0.49**	2.26**	0.19*	1.04	0.25*	0.18	88	76*	20	4.7*
5	0.77	2.17	0.22	0.86	0.30	0.17	89	84	20	4.6
10	0.91	2.11	0.23	0.93	0.33	0.18	87	74	20	5.0
15	0.94	2.03	0.21	0.87	0.35	0.17	84	77	20	4.9
20	1.00	1.99	0.20	0.85	0.33	0.16	83	69	20	5.3
R^2	0.73	0.77	0.58	0.39	0.67	0.23	0.40	0.66	0.30	0.51

[+] Means are expressed as percent or ppm of dry weight of TVD leaf minus midrib.

[‡] Means of 25 observations. Means in the same column followed by the same letter are not signficantly different (LSD) at the 5% level of probability.

[++] Means of 15 observations.

[*] Regression is significant at 0.05.

[**] Regression is significant at 0.01.

Table 15. Influences of rate and type of soluble silicates on nutrient concentration in sugarcane leaves+ (September, 1979, sampling)

Silicate material‡	Si	N	P	K	Ca	Mg	Fe	Mn	Zn	Cu
	----	----	----	%	----	----	----	----	ppm	----
TVA	0.76a	2.05b	0.16a	0.74a	0.30a	0.19a	87a	70a	19a	1.9a
Fla	0.75a	2.13a	0.17a	0.69a	0.30a	0.18a	88a	52c	20ba	1.9a
Cement	0.78a	2.08ab	0.14b	0.71a	0.31a	0.18a	84a	60b	21b	2.1a
Rate++ (t/ha)										
0	0.47**	2.15*	0.14**	0.76	0.26	0.18	86	53**	18	1.7*
5	0.74	2.11	0.16	0.67	0.31	0.18	90	69	20	1.7
10	0.82	2.11	0.18	0.75	0.31	0.18	89	62	20	2.2
15	0.88	2.06	0.18	0.70	0.32	0.18	84	63	20	1.9
20	0.90	2.01	0.14	0.69	0.32	0.18	82	58	20	2.3
R^2	0.73	0.51	0.56	0.36	0.43	0.21	0.34	0.64	0.41	0.41

+Means are expressed as percent or ppm of dry weight of TVD leaf minus midrib.

‡Means of 25 observations. Means in the same column followed by the same letter are not significantly different (LDS) at the 5% level of probability.

++Means of 15 observations.

*Regression is significant at 0.05.

**Regression is significant at 0.01.

Table 16. Influences of rate and type of soluble silicates on nutrient concentration in sugarcane leaves+ (June, 1979, sampling)

Silicate material‡	Si	N	P	K	Ca	Mg	Fe	Mn	Zn	Cu
TVA	0.57b	2.06a	0.28b	1.17a	0.39b	0.17a	66a	57a	16a	4.9a
Fla	0.69a	2.04a	0.30a	1.13a	0.43a	0.16a	68a	59a	14b	3.9b
Cement	0.60b	2.03a	0.28b	1.18a	0.37b	0.16a	68a	53b	16a	4.0b
Rate++ (t/ha)										
0	0.35**	2.30**	0.32**	1.52**	0.32**	0.18*	87**	76**	17*	3.0**
5	0.50	2.13	0.30	1.16	0.37	0.17	65	72	15	3.7
10	0.64	1.96	0.29	1.02	0.41	0.15	58	65	14	4.4
15	0.89	1.87	0.27	0.95	0.39	0.14	58	50	13	4.9
20	0.73	1.95	0.29	1.14	0.49	0.17	67	27	16	5.4
R^2	0.74	0.84	0.75	0.80	0.64	0.40	0.80	0.82	0.65	0.81

+Means are expressed as percent or ppm of dry weight of TVD leaf minus midrib.

‡Means of 25 observations. Means in the same column followed by the same letter are not significantly different (LSD) at the 5% level of probability.

++Means of 15 observations.

*Regression is significant at 0.05.

**Regression is significant at 0.01.

Silicon. Leaf Si was significantly increased by the application of soluble silicates. In the June sampling of the plant crop leaf Si was doubled when 10 MT/ha of Fla slag was applied, and it continued to increase with further applications of the material (Figure 8). Fla slag enhanced leaf Si more than TVA slag and cement. This was attributed to the higher Si level in Fla slag compared to the other two materials (Table 2). Application of cement enhanced leaf Si to about the same extent as TVA slag, although the latter contains twice as much Si as the former. This was attributed to the fine nature and high solubility of cement. In the ratoon crop maximum leaf Si was obtained when 17 and 13 MT/ha of Fla and TVA slags were applied, respectively, whereas leaf Si showed a linear increase with cement (Figure 9). It may be that high rates of Fla and TVA slags changed soil pH to the point that silicates were not reactive.

Nitrogen. Leaf N of the plant crop showed a linear decrease with the application of silicate materials (Figure 10). Fla slag decreased leaf N more than TVA slag. The decrease in leaf N may be attributed to dilution effect as a result of increased phytomass production due to Si and/or to soil reactions that resulted in reduced uptake of N.

Phosphorus. Leaf P was appreciably increased by Fla slag, slightly increased by TVA slag, and slightly reduced by cement (Figure 11). This was directly related to the amount of P contained in each material (Table 2). Addition of

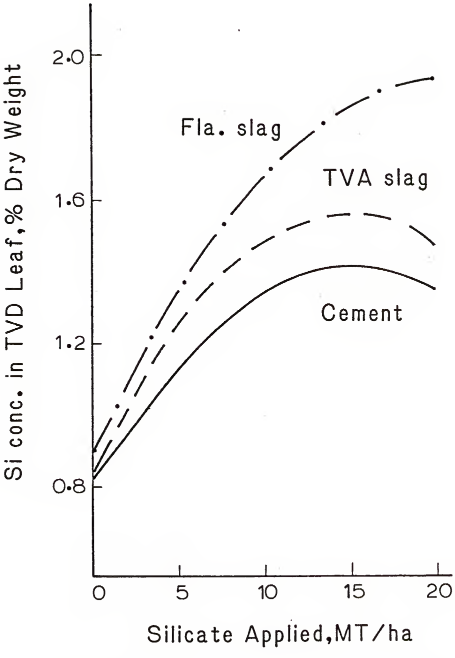

Figure 8. Influence of different rates of 3 soluble silicates on leaf silicon (plant crop)

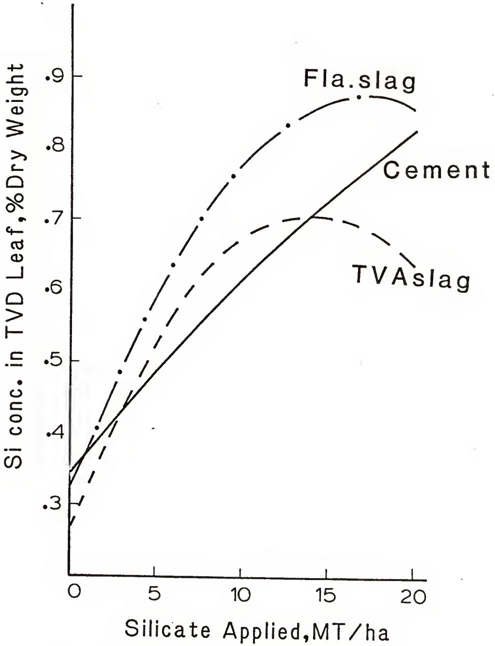

Figure 9. Influence of different rates of 3 soluble silicates on leaf silicon (ratoon crop)

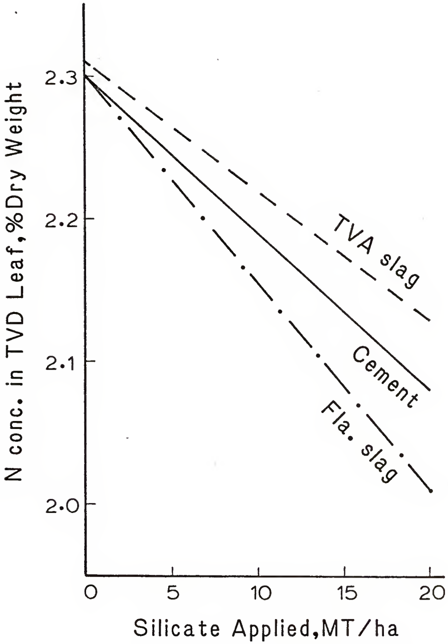

Figure 10. Influence of different rates of 3 soluble silicates on leaf nitrogen (plant crop)

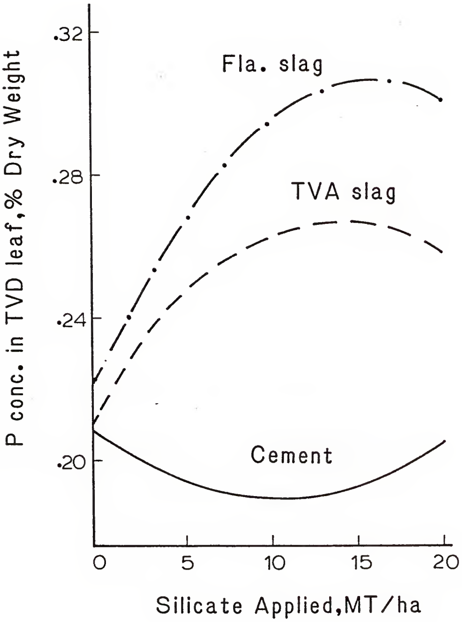

Figure 11. Influence of different rates of 3 soluble silicates on leaf phosphorus (plant crop)

20 MT/ha of Fla slag, TVA slag, and cement added to the soil 256, 128, and 0 Kg/ha of P_2O_5, respectively (Table 3). Cement did not increase leaf P simply because it contains no P. On the other hand, Fla and TVA slags contain P and thereby increased leaf P. This interpretation is inconsistent with the theory that addition of soluble silicates solubilizes soil P (Tuilin, 1936; Toth, 1939; Cooke, 1956; Raupach and Piper, 1959; Teranishi, 1968; Roy et al., 1971) and improves P nutrition of the plant (Silva, 1971; Kudinova, 1974). However, it agrees with the findings of Gascho and Andreis (1974) who reported that leaf P was not appreciably affected by addition of TVA slag. In another report Gascho (1978) stated that TVA slag and Na silicate reduced P concentration in the above-ground plant tissue. Ayres (1966) reported that increased P uptake by sugarcane with TVA slag additions was due to higher yields resulting from the use of the material rather than the other way around. Fla slag offers a good substitute to TVA slag, particularly in low P soils. In the ratoon crop, leaf P was sharply decreased by TVA slag and cement and unaffected by Fla slag (Figure 12). The decrease in leaf P was attributed to dilution effect as a result of higher dry matter production due to Si. Cement and TVA slag did not supply the ratoon crop with P because the former is devoid of P and the P in the latter was taken up by the plant crop. Although Fla slag did not increase leaf P in the ratoon crop, it did not decrease it in spite of the dilution effect. This indicates that Fla slag

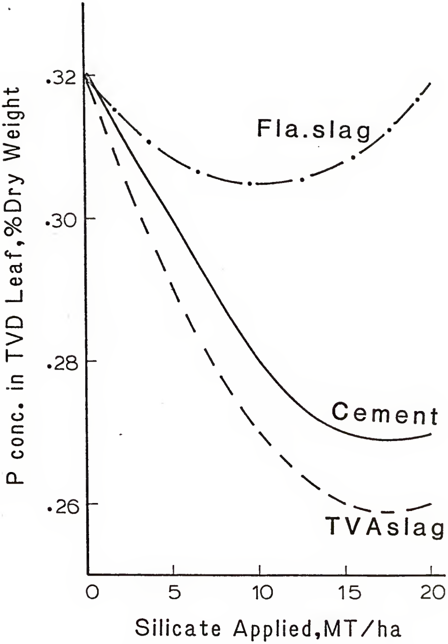

Figure 12. Influence of different rates of 3 soluble silicates on leaf phosphorous (ratoon crop)

continued to add P to the soil solution during the ratoon crop. This is a further evidence that increased plant and soil P by soluble silicates is not due to solubilization of soil P by such materials, but to the inherent amount of P they contain.

Potassium. Leaf K was significantly decreased by the addition of silicates, although there was no difference among the three materials. Decrease in leaf K was directly related to increase in cane tonnage caused by Si, i.e. to dilution effect. In the ratoon crop, leaf K was decreased when cane yield was increased and vice versa (Figure 13). Wong You Cheong et al. (1973) reported no effect on leaf K when 200 ppm Si was applied to sugarcane grown in a nutrient solution. The authors also reported no increase in dry matter production. This supports the interpretation that Si causes reduction in leaf K due to dilution effect.

Calcium and Magnesium. Leaf Ca was linearly enhanced by silicate materials, especially by cement (Figure 14). This is attributed to the high level of Ca in all three materials, especially cement (Table 2). On the other hand, leaf Mg was decreased by the addition of silicates (Figure 15). There was no difference among the three silicates used in the study. Reduction in leaf Mg by the addition of silicates has been reported by many investigators (Wong You Cheong et al., 1973; Clements et al., 1974; Clements, 1980). This is caused in part by increase in soil pH.

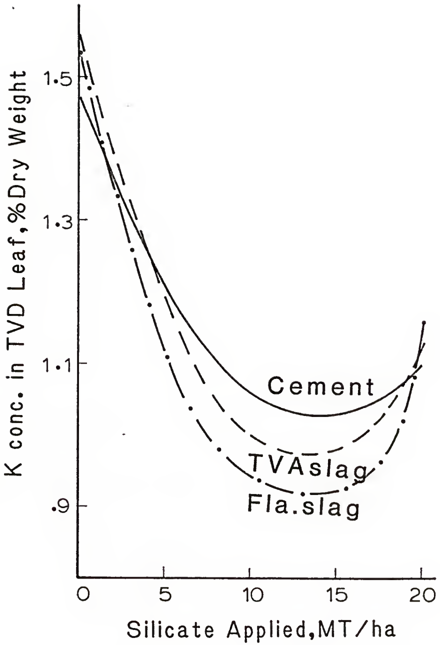

Figure 13. Influence of different rates of 3 soluble silicates on leaf potassium (ratoon crop)

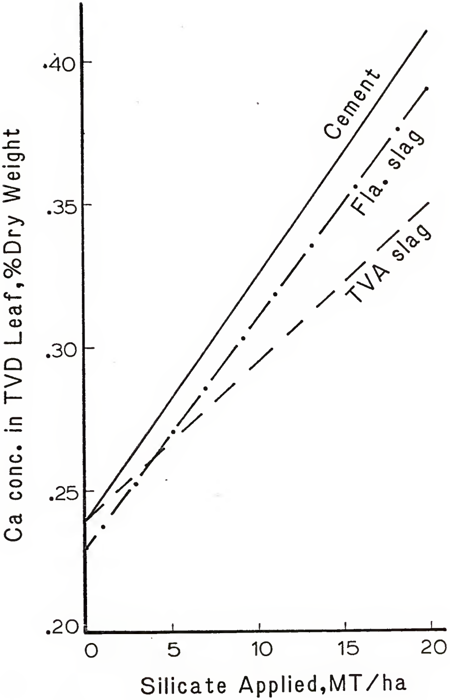

Figure 14. Influence of different rates of 3 soluble silicates on leaf calcium (plant crop)

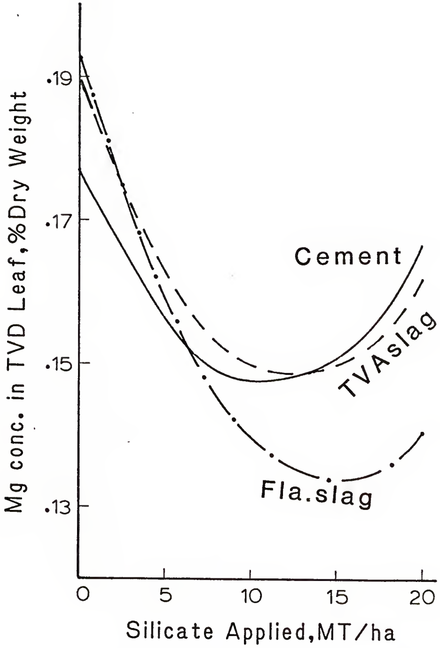

Figure 15. Influence of different rates of 3 soluble silicates on leaf magnesium (plant crop)

Micronutrients. Concentrations of Fe, Mn, and Zn in sugarcane leaves were substantially reduced by the addition of soluble silicates. On the other hand, Cu concentration was markedly enhanced. The reduction of leaf Fe, Mn, and Zn as a result of Si application has been reported by many workers (Clements, 1965b; Clements et al., 1967, 1974; Gascho, 1978; Samuels and Alexander, 1969). Several mechanisms by which soluble silicates reduce plant Fe and Mn have been proposed. They include decrease in Fe and Mn uptake by plants (Okuda and Takahashi, 1965), dilution effect due to the increased growth associated with Si addition, increase in Fe and Mn tolerance of plants by Si (Horst and Marschner, 1978), and soil pH alterations (Samuels and Alexander, 1969). Clements et al. (1974) reported that if Fe and Mn inside the leaf did not encounter certain minimum levels of Si and/or Ca, they localided in such concentrations that they caused necrosis. One of the effects of the silicate materials used in this study was to precipitate Fe and Mn in the soil solution. Toxic elements common in soil solutions include Fe^{++}, Mn^{++}, Zn^{++} and other cations. The silicates resulting with each of these cations are very insoluble. Thus, Fe, Mn, and Zn concentrations in the leaf were reduced due to the application of soluble silicates as a result of precipitation of these elements. The enhancement of plant Cu due to the addition of soluble silicates has been reported by Clements (1980) and Gascho (1978). Soluble silicates, especially slags, seem to increase Cu uptake by sugarcane (Figure 16). This

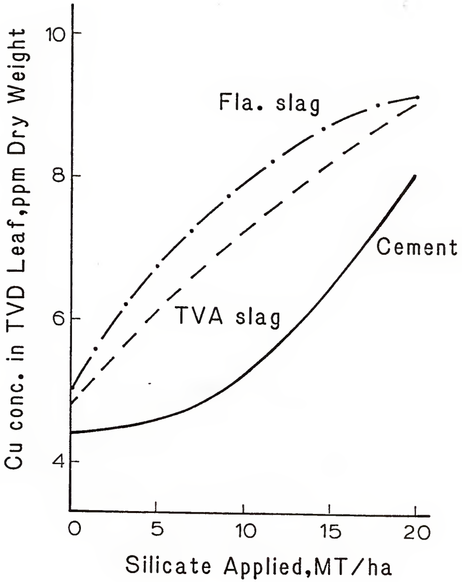

Figure 16. Influence of different rates of 3 soluble silicates on leaf copper (plant crop)

is of special importance in Florida because organic soils require application of Cu salts to field-grown sugarcane (Allison et al., 1927). Florida peat soils when first planted to cane, produced "droopy top disease," which was corrected by applying 112 Kg of $CuSO_4$/ha many years ago.

Cane and Sugar Yields

Cane and sugar yields were substantially increased by the application of soluble silicates (Tables 10 and 11). In the plant crop, cane and sugar yields were increased by all levels of Si (Figures 17 and 18), although there was no difference among the three materials. In the ratoon crop, Fla slag was the best in increasing cane and sugar yields, followed by cement, and then TVA slag (Figures 19 and 20). Application of up to 15 MT/ha of soluble silicates enhanced cane and sugar yields, but at the 20-ton level the silicates caused severe chlorosis and sharp decline in yield (Figures 19 and 20). It may be that high levels of silicate materials increased soil pH to the point that silicate was not reactive. Increases in cane and sugar yields due to soluble silicates were the result of increased number of millable stalks and increased plant size caused by soluble silicates. Application of soluble silicates did not affect pol reading or percent sugar. The yield data indicate that Si is essential for the growth of sugarcane, and point to its role in the production of more plants per area (tillering ability), more efficient photosynthesis, and prevention of leaf freckling.

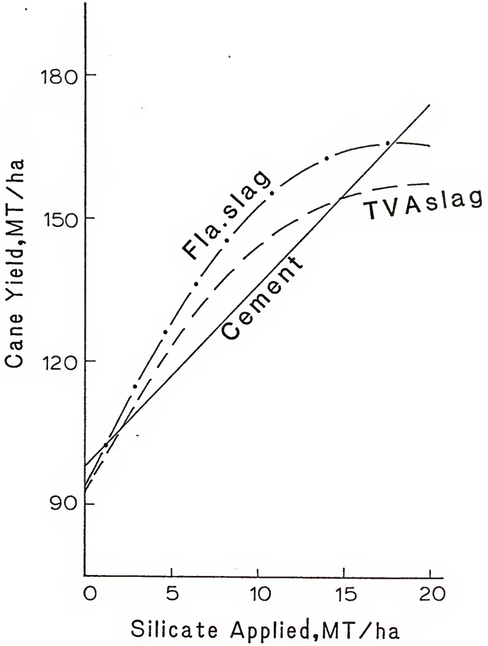

Figure 17. Influence of different rates of 3 soluble silicates on cane yield (plant crop)

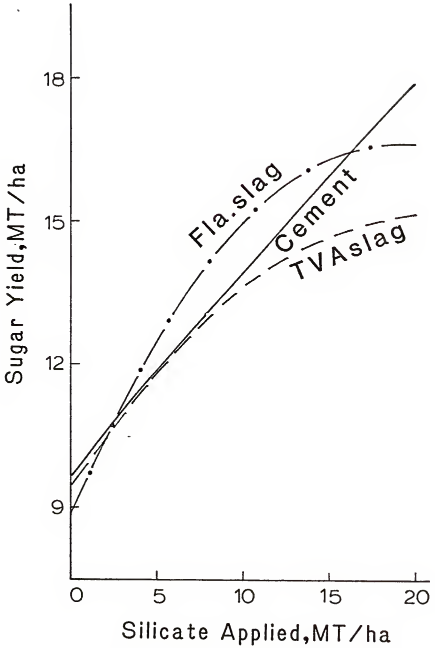

Figure 18. Influence of different rates of 3 soluble silicates on sugar yield (plant crop)

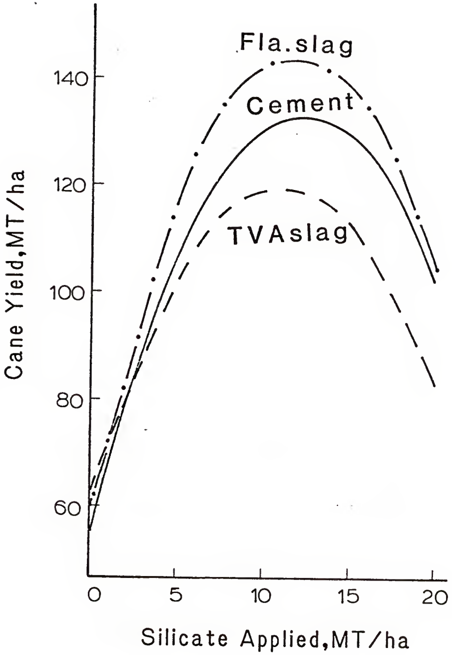

Figure 19. Influence of different rates of 3 soluble silicates on cane yield (ratoon crop)

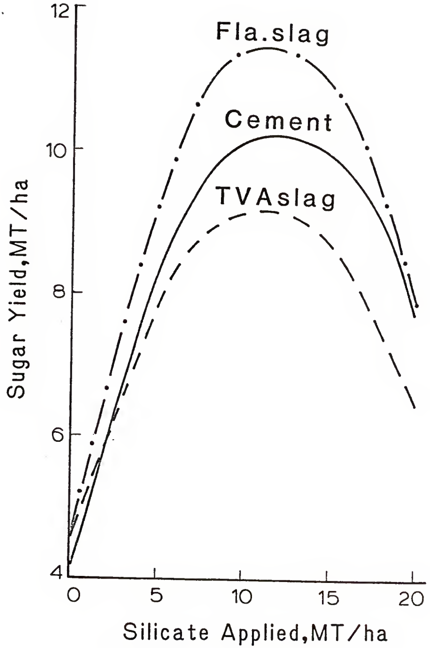

Figure 20. Influence of different rates of 3 soluble silicates on sugar yield (ratoon crop)

Soil Composition

The influence of soluble silicates on soil composition is shown in Tables 17 and 18. All soil parameters, especially pH and Si, were substantially enhanced, except soil Mg which was lowered.

Addition of 20 MT/ha of soluble silicates increased soil pH from 4.5 to 5.3 and from 4.4 to 6.1 in plant and ratoon crops, respectively. In both samplings the increase in pH was linear (Figure 21). At such pH levels, particularly in the ratoon crop, micronutrients in the soil solution may precipitate and thus become unavailable to plant roots. This may explain the low levels of Fe, Mn, and Zn in sugarcane leaves due to soluble silicates. Cement increased soil pH more than both slags in the plant crop and more than TVA slag in the ratoon crop. This is because cement contains a considerable quantity of Ca. Fla slag increased soil pH more than TVA slag although the latter has more Ca than the former (Table 2). This indicates that Fla slag is more soluble than TVA slag under similar soil conditions.

Soil Si was substantially increased due to additions of soluble silicates. All materials resulted in a linear increase (Figure 22). Fla slag solubilized more Si in the soil solution than the other two materials mainly because of its higher Si content. Cement and TVA slag solubilized approximately similar levels of Si in the soil solution although the latter contains twice the amount of Si in the former. This again points to the low solubility of silicate in TVA slag.

Table 17. Influences of rate and type of soluble silicates on soil parameters (July, 1979, sampling)

Silicate material+	pH	Si	P	K	Ca	Mg
		ppm	----------Kg/ha-----------			
TVA	4.8b	28b	21a	87a	1960b	197a
Fla	4.9b	38a	22a	68b	2330a	200a
Cement	5.1a	32b	14b	72b	2540a	208a
Rate‡ (t/ha)						
0	4.5**	12**	15**	59*	1520**	220*
5	4.8	26	19	73	2040	210
10	5.0	37	20	91	2420	200
15	5.0	37	21	72	2420	190
20	5.3	52	19	83	2990	160
R^2	0.62	0.79	0.80	0.34	0.63	0.37

+Means of 25 observations. Means in the same column followed by the same letter are not significantly different (LSD) at the 5% level of probability.

‡Means of 15 observations.

*Regression is significant at 0.05.

**Regression is significant at 0.01.

Table 18. Influences of rate and type of soluble silicates on soil parameters (September, 1979, sampling)

Silicate material[+]	pH	Si	P	K	Ca	Mg
		ppm	-----------Kg/ha----------			
TVA	5.2b	17b	24a	58a	2680c	225a
Fla	5.5a	19a	24a	55a	3950a	219a
Cement	5.5a	17b	17b	55a	3720b	220a
Rate[‡] (t/ha)						
0	4.4**	9**	18**	40**	1620**	240**
5	5.0	13	20	52	2640	250
10	5.6	21	25	61	3710	210
15	5.8	22	25	74	4340	212
20	6.1	26	21	55	4920	190
R^2	0.89	0.88	0.51	0.55	0.97	0.75

[+]Means of 25 observations. Means in the same column followed by the same letter are not significantly different (LSD) at the 5% level of probability.

[‡]Means of 15 observations.

**Regression is significant at 0.01.

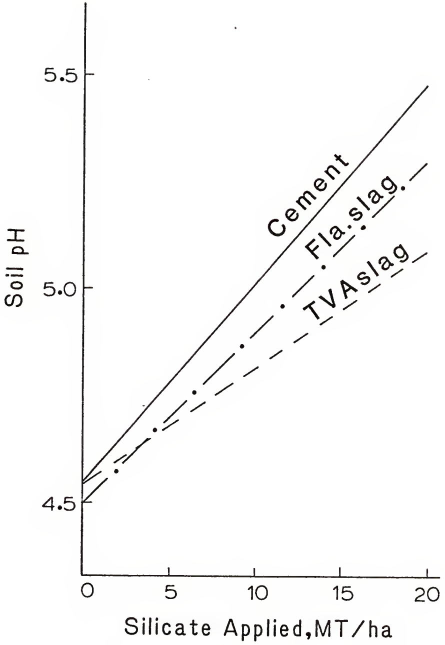

Figure 21. Influence of different rates of 3 soluble silicates on soil pH (plant crop)

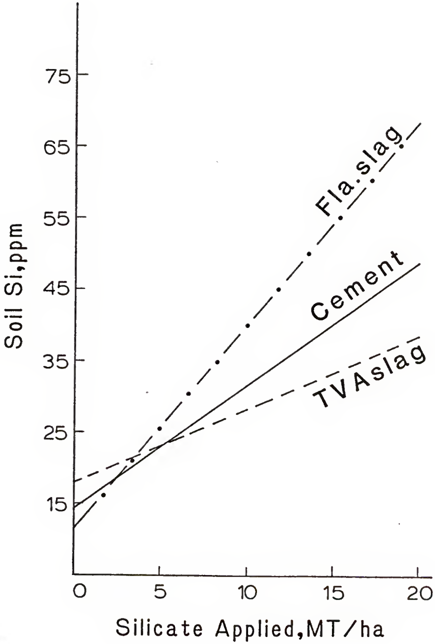

Figure 22. Influence of different rates of 3 soluble silicates on soil silicon (plant crop)

Soil P was appreciably enhanced by Fla and TVA slags but was slightly reduced by cement (Figure 23). This is directly related to the amount of P each material contains (Table 2). Application of 20 MT/ha of Fla slag, TVA slag, and cement added to the soil 256, 128, and 0 kg/ha of P_2O_5, respectively. This is inconsistent with the theory that soluble silicates solubilize soil P. Plant and soil data of this study tend to discredit this theory. Enhancement of soil and plant P is due to addition of P to the soil solution when soluble silicates are added, rather than to solubilization of inherent soil P. This is why cement in this study and Na silicate in the previous study did not increase either soil or plant P. Both materials contain no P. Gascho (1978) reported similar effects of Na silicate on soil P. On the other hand both Fla and TVA slags increased soil and plant P because they contain approximately 1.2 and 0.6% P_2O_5, respectively.

Soil K and Ca were increased by soluble silicates while soil Mg was reduced. TVA slag increased soil K more than Fla slag and cement because it contains 0.7% K_2O while the other two materials contain no K_2O (Table 2). Soil Mg was lowered by soluble silicates due to soil pH increases.

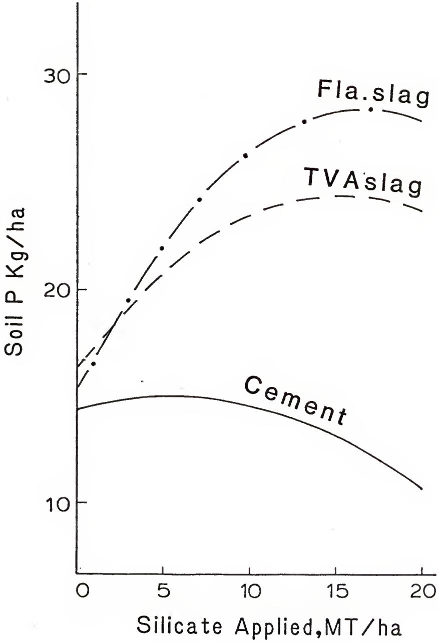

Figure 23. Influence of different rates of 3 soluble silicates on soil phosphorous (plant crop)

CHAPTER 5

SUMMARY AND CONCLUSIONS

A greenhouse experiment was conducted to investigate the effect of enhanced UV-B irradiance and Si on the growth and dry-matter yield of sugarcane. Although supplemental UV-B irradiance reduced plant height, stem diameter, leaf area, and dry-matter yield, it did not induce sugarcane leaf freckling. Cane grown outside the greenhouse without Si was severely freckled although it was not exposed to artificial UV-B radiation. This indicates that sugarcane leaf freckling is caused by something other than UV-B radiation. Addition of Si substantially improved the resistance of sugarcane to stem borer. Outside the greenhouse, where light conditions were adequate, Si enhanced the tillering ability of sugarcane. Plants grown inside the greenhouse did not produce tillers even with the top rate of Si. The effectiveness of Na silicate was attributed to its high solubility and strong alkalinity.

A field experiment was conducted to study the response of sugarcane to several levels of three soluble silicates. The materials corrected sugarcane leaf freckling and increased cane and sugar yields irrespective of their composition. Soluble silicates function in the soil solution as well as within the plant.

Plant and soil data discredit the theory that soluble silicates solubilize soil P. Only the silicates which contain P enhance soil and plant P.

Plant and yield data indicate that Si is essential for the growth of sugarcane; and that sugarcane leaf freckling is the Si-deficiency symptom.

Since the use of TVA slag might be banned by EPA, Fla slag provides a good substitute for sugarcane growers in South Florida. It has the following advantages over TVA slag: (a) has 50% more Si, (b) contains twice as much P, and (c) is more soluble than TVA slag.

Cement is an excellent source of Si, but it has three drawbacks: (a) it is very expensive compared to the slags, (b) its speed of "setting up" prevents its being piled up in a field prior to spreading, and (c) its high content of CaO may induce localized deficiencies of Mg, Mn, Fe, etc.

From 5 to 15 MT/ha of soluble silicates should be applied to sugarcane grown in organic soils depending on the original Si status of the soil and the variety to be grown.

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I certify that I have read this study and that in my opinion it conforms to acceptable standards of scholarly presentation and is fully adequate, in scope and quality, as a dissertation for the degree of Doctor of Philosophy.

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